Impact of interference effects on BSM Higgs production processes

19th Workshop of the LHC Higgs Working Group

Georg Weiglein, DESY & University of Hamburg, 11/2022

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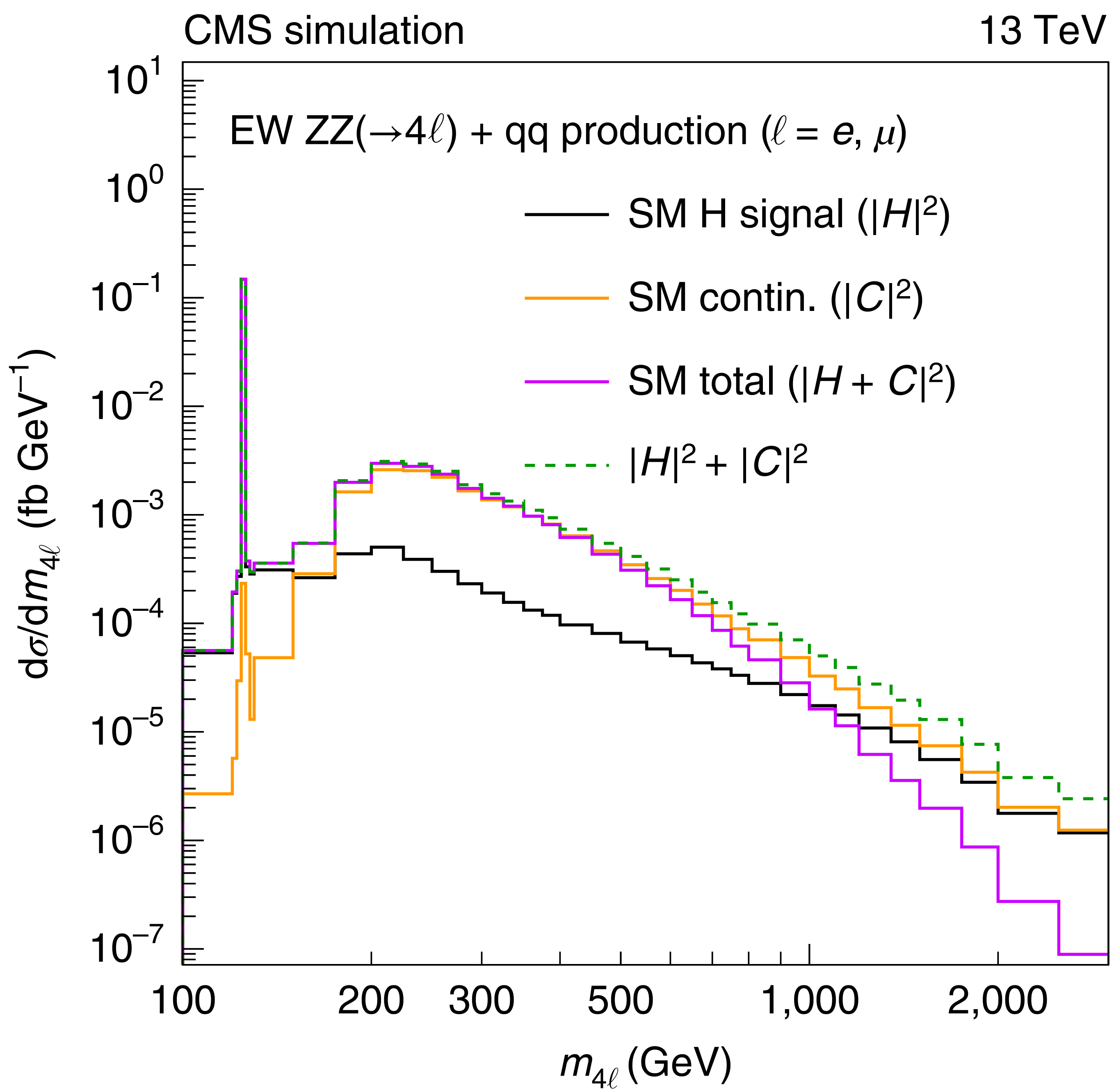
DESY.

Interference effects for SM Higgs in H → ZZ → 4l

[CMS Collaboration '22]

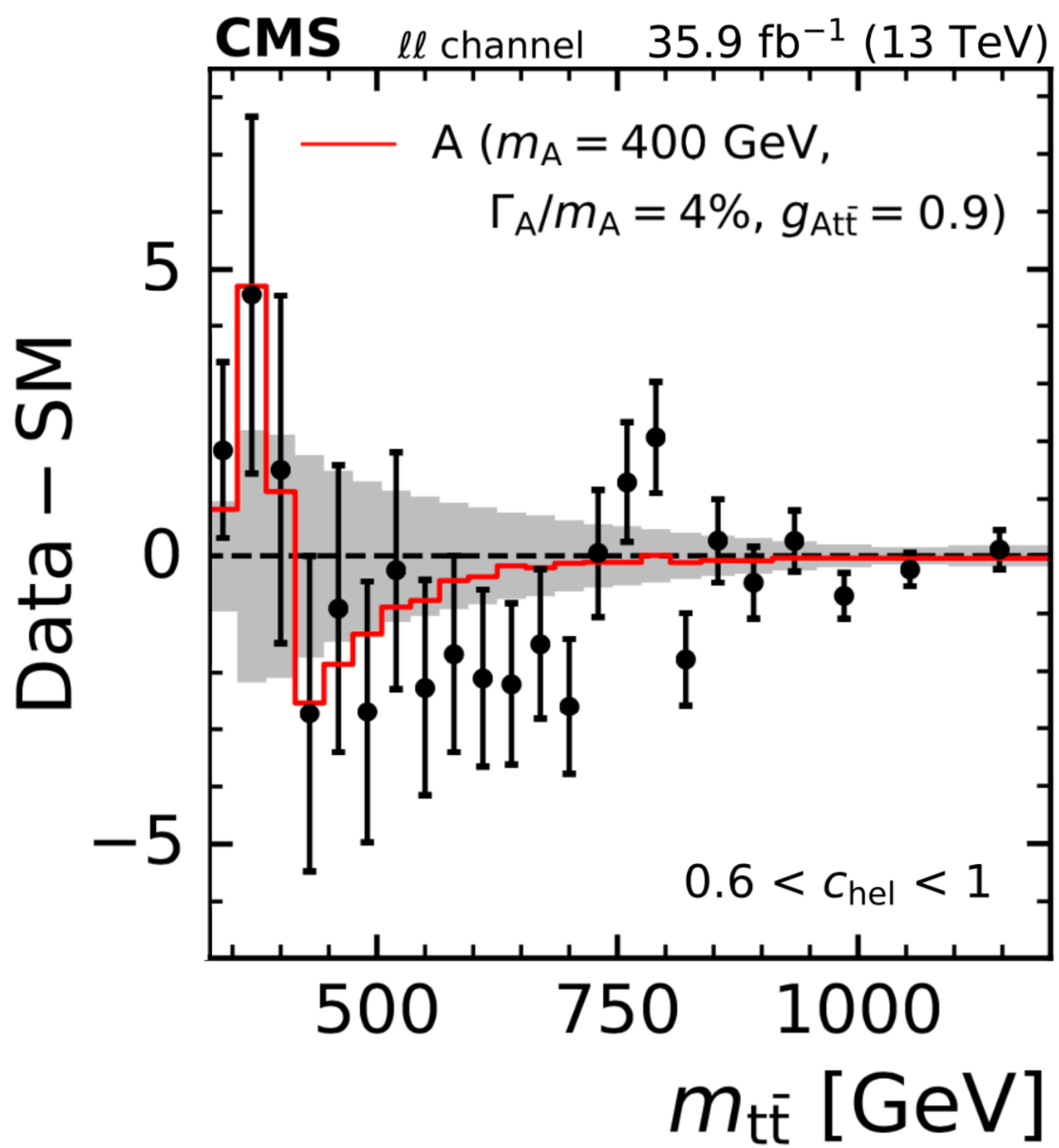


} Impact of signal-background interference

⇒ Sizeable interference contributions in H → ZZ* despite the small width (≈ 4 MeV) of the SM Higgs: off-shell Higgs traded for off-shell Z

Interference effects in BSM Higgs searches

Example: CMS search for H, A → tt *[CMS Collaboration '19]*



⇒ Characteristic ``peak-dip” structure expected from signal-background interference

Search for BSM Higgs bosons that can mix with each other (almost mass-degenerate Higgses H, A)

Total cross section (signal-signal contribution):

$$\sigma_{\text{tot}} = \sigma(b\bar{b}H) + \sigma(b\bar{b}A) \text{ (incoherent sum)}$$

holds only in the $\mathcal{CP}$-conserving case

But: in reality we don't know whether $\mathcal{CP}$ in the Higgs sector is conserved or not

Example: MSSM with complex parameters

Complex parameters $\Rightarrow$ loop corrections induce $\mathcal{CP}$-violation

Two Higgs states, nearly mass degenerate, large mixing

$\Rightarrow$ Large (destructive) interference possible

Search for heavy Higgs bosons at the LHC: impact of interference effects

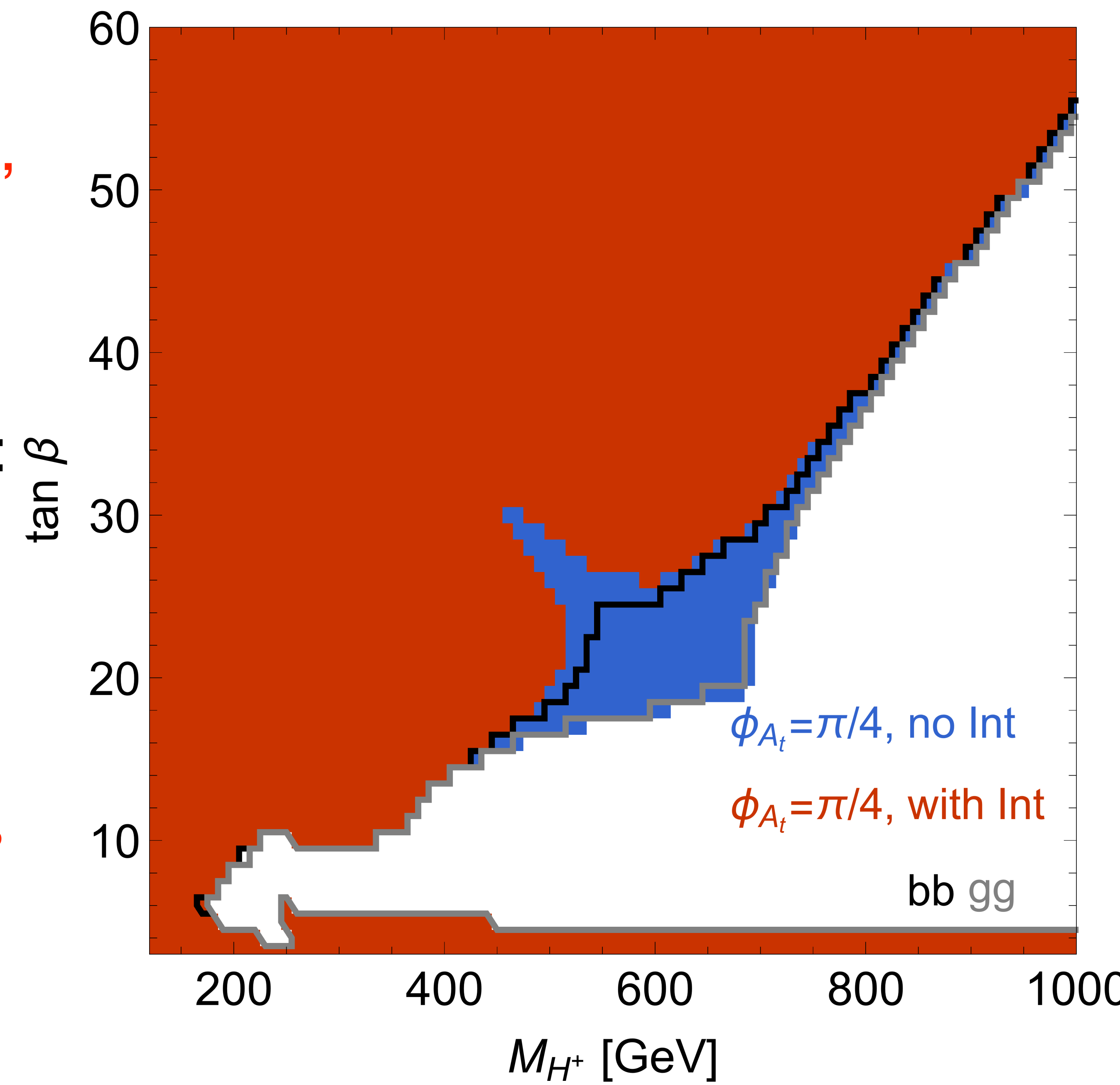
[E. Fuchs, G. W. '17]

Exclusion limits from neutral Higgs searches in the MSSM with and without interference effects:

CP-violating case, $\phi_{A_t} = \pi / 4$

H, A are nearly mass degenerate: large mixing possible in CP-violating case!

Incoherent sum is not sufficient!



HiggsBounds

[H. Bahl et al. '22]

$m_h^{\mathrm{mod}+}$ scenario, μ = 1000 GeV

⇒ Large CP-violating interference effects possible

$M_{h1}{}^{125}$(CPV) benchmark scenario

[E. Bagnaschi et al. '18]

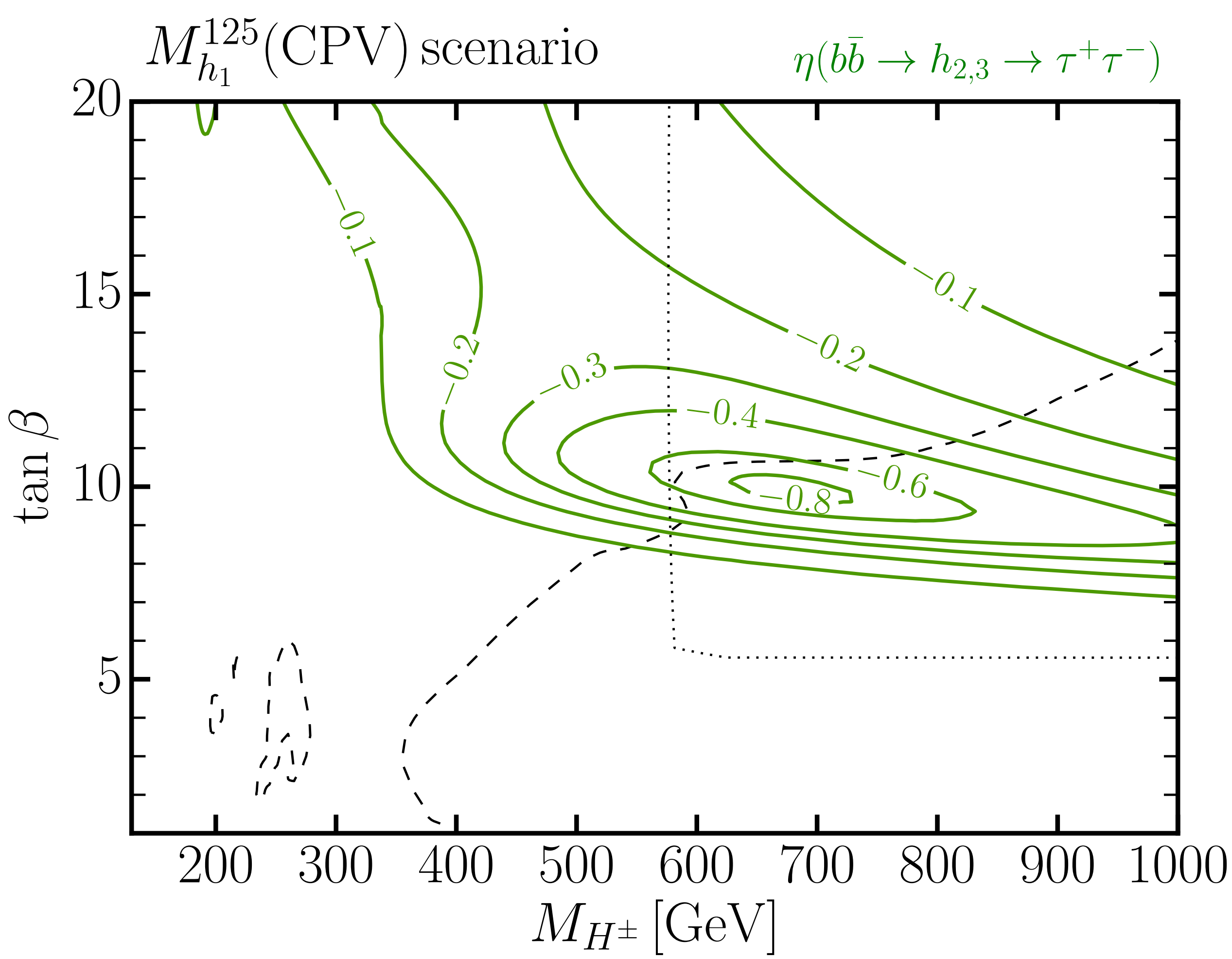
$M_{\text{SUSY}} = 2\,\text{TeV}, \mu = 1.65\,\text{TeV},$

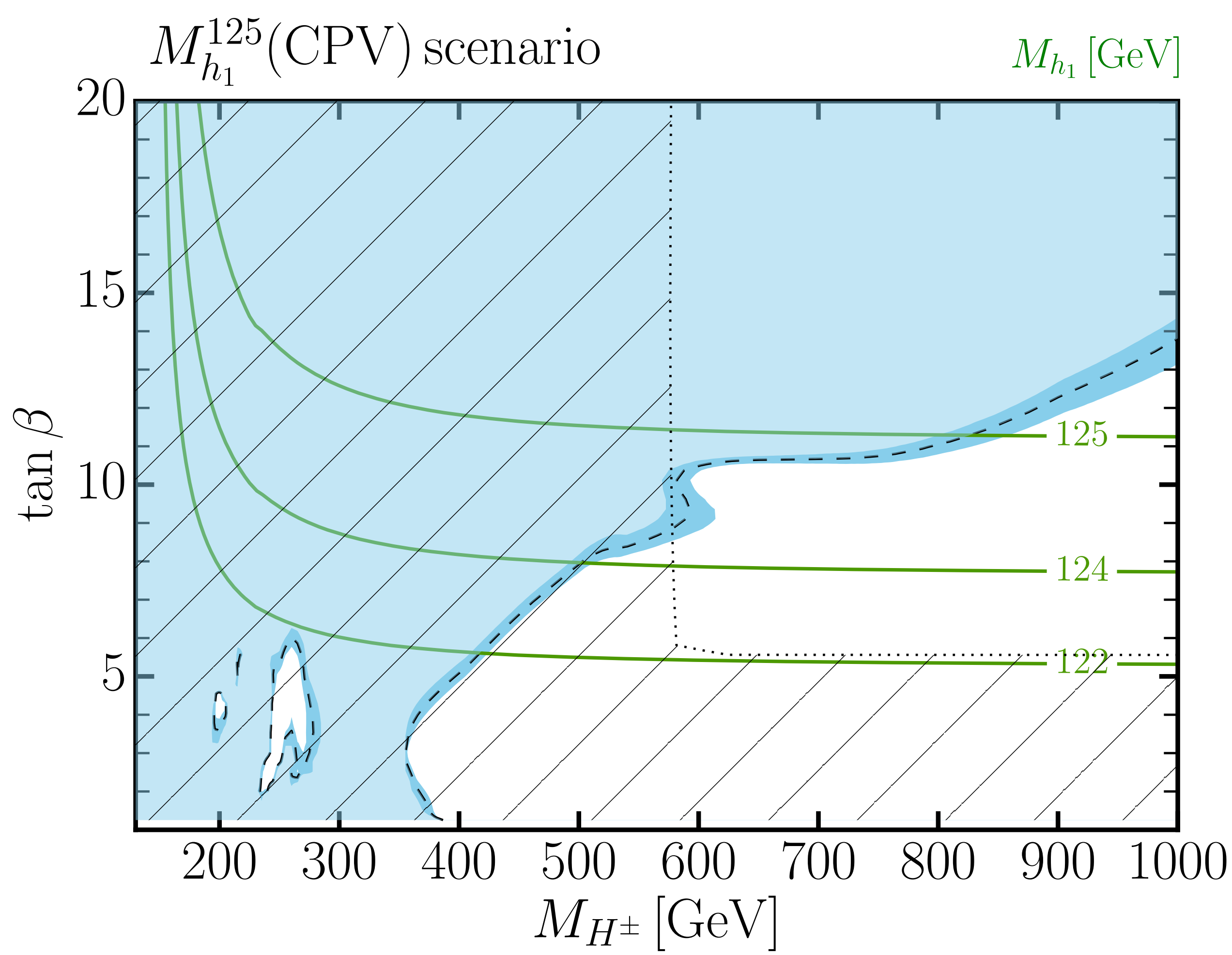
$M_1 = M_2 = 1\,\text{TeV}, \;\; M_3 = 2.5\,\text{TeV},$

$|A_t| = A_{b,\tau} = \mu \cot\beta + 2.8\,\text{TeV},$

$\phi_{A_t} = 2\pi/15$

- ✓ $M_{h_1} = 125.09 \pm 3\,\text{GeV}$ FeynHiggs
- ✓ h_1 SM-like HiggsSignals
- ✓ additional searches HiggsBounds
- ✓ EDM 2013 × EDM 2018

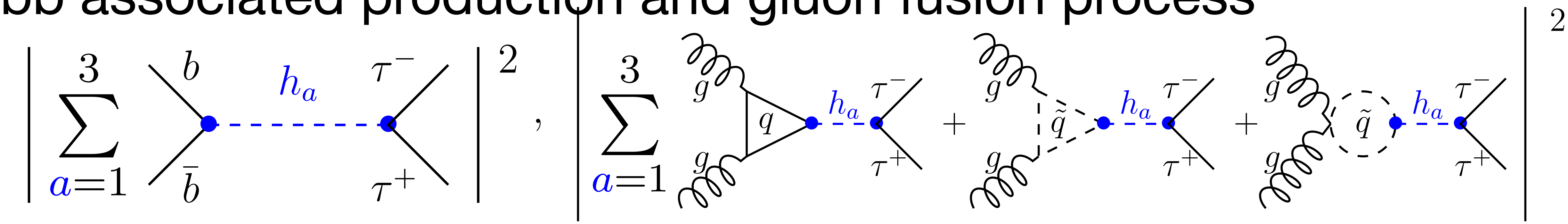




⇒ Unexcluded "bay" because of destructive h_2—h_3 interference of up to −95%

Signal-signal interference contributions

Example: three neutral mass eigenstates h_1, h_2, h_3, $\tau^+\tau^-$ final state, bb associated production and gluon fusion process



+ higher-order contributions

Signal-signal interference contributions can be large for $\Delta M_{ij} = |M_i - M_j| \leqq \Gamma_i + \Gamma_j$

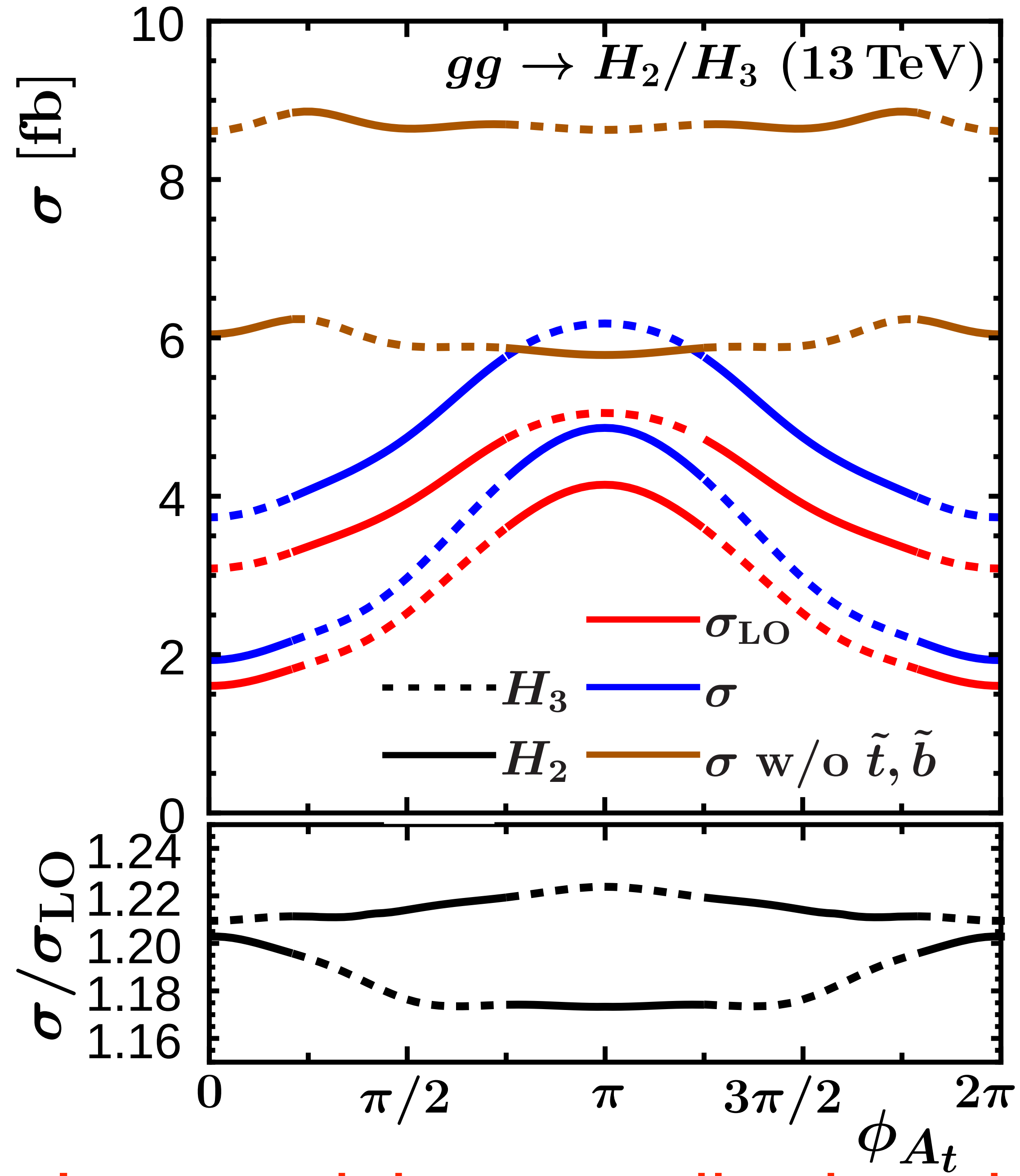
Typical situation in searches for heavy BSM Higgs bosons:
$M_1 \approx 125$ GeV, $M_2 \approx M_3 \gg M_1$

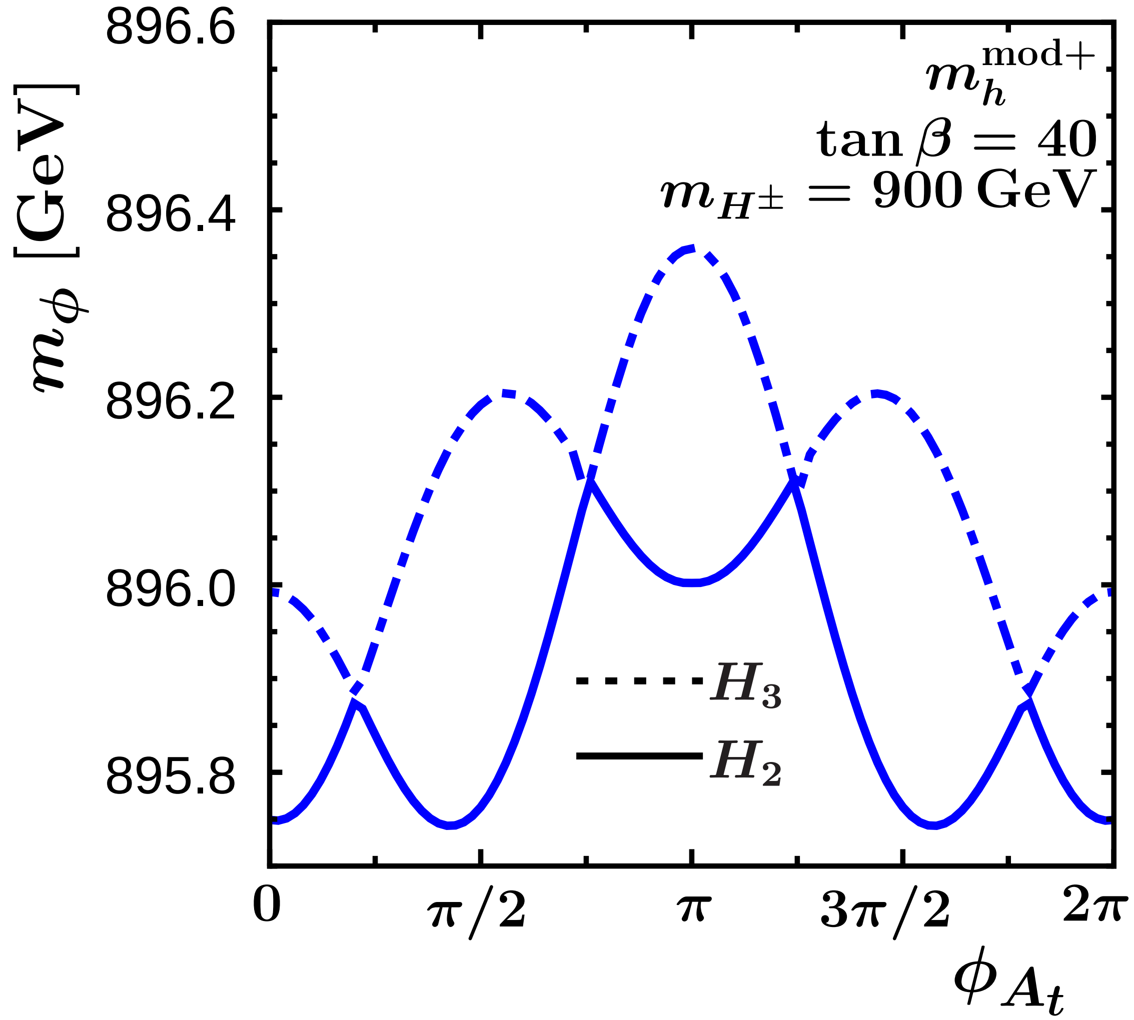
⇒Large signal-signal effects possible if h_2, h_3 mix with each other, resonance-type behaviour!

Higgs production via gluon fusion in the MSSM with CP-violation: *SusHiMi* code

[S. Liebler, S. Patel, G. W. '16]

gg → $H_2 H_3$, dependence on phase ϕ_{At}:





Only production process shown here

⇒ Large mixing contributions between the mass eigenstates H_2, H_3
Full result for σ x BR needs to incorporate interference contribution

Theoretical description

Extended Higgs sectors: several Higgs states which can mix with each other

Higgs-mass prediction from propagator matrix

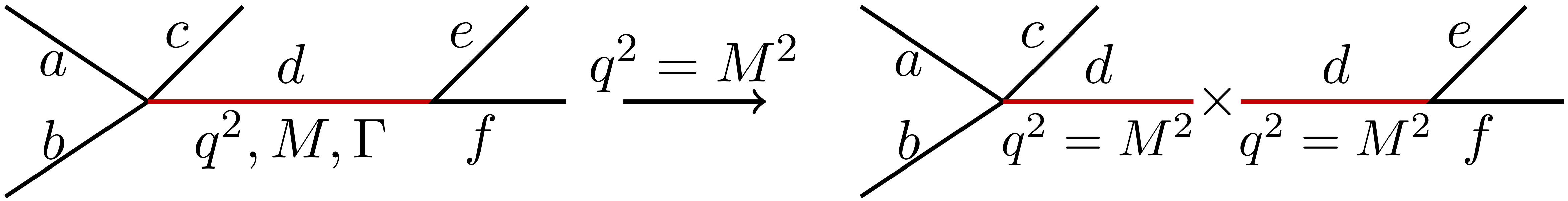
Example:

MSSM with complex parameters; two Higgs doublets, three neutral states

Lowest order: h, H (CP-even) and A (CP-odd)
CP violation induced by loop corrections:
Mixing of $h, H, A \longrightarrow$ mass eigenstates h_1, h_2, h_3

Standard narrow-width approximation (NWA): interference effects are not taken into account

- simplify complicated process by factorisation: production $\times$ decay



- on-shell production and decay of particle with mass M:

$$\sigma_{ab\to cef} \approx \sigma_{ab\to cd}(q^2 = M^2) \cdot BR_{d\to ef}$$

- useful in particular for BSM with extended spectrum

Conditions and limitations of standard NWA

- narrow width $\Gamma \ll M$, otherwise off-shell effects e.g. [Gigg, Richardson '08]
- production & decay open, away from thresholds e.g. [Kauer '08]
- non-factorisable corrections small e.g. [Denner, Dittmaier, Roth '98]
- no interference with other processes

e.g. [Reuter '07], [Berdine, Kauer, Rainwater '07], [Kalinowski, Kilian, Reuter, Robens, Rolbiecki '08]

Extended Higgs sector phenomenology: mixing between three neutral Higgs bosons

Mixing between h, H, A

⇒ loop-corrected masses obtained from propagator matrix

$$\Delta_{hHA}(p^2) = -\left(\hat{\Gamma}_{hHA}(p^2)\right)^{-1}, \quad \hat{\Gamma}_{hHA}(p^2) = i\left[p^2 \mathbb{1} - \mathrm{M_n}(p^2)\right]$$

where (up to sub-leading two-loop corrections)

$$\mathrm{M_n}(p^2) = \begin{pmatrix} m_\mathrm{h}^2 - \hat{\Sigma}_{hh}(p^2) & -\hat{\Sigma}_{hH}(p^2) & -\hat{\Sigma}_{hA}(p^2) \\ -\hat{\Sigma}_{hH}(p^2) & m_\mathrm{H}^2 - \hat{\Sigma}_{HH}(p^2) & -\hat{\Sigma}_{HA}(p^2) \\ -\hat{\Sigma}_{hA}(p^2) & -\hat{\Sigma}_{HA}(p^2) & m_\mathrm{A}^2 - \hat{\Sigma}_{AA}(p^2) \end{pmatrix}$$

⇒ Higgs propagators: $\Delta_{ii}(p^2) = \dfrac{i}{p^2 - m_i^2 + \hat{\Sigma}_{ii}^{\mathrm{eff}}(p^2)}$

Determination of the Higgs masses from the complex poles

$$\hat{\Sigma}^{\rm eff}_{ii}(p^2) = \hat{\Sigma}_{ii}(p^2) - i\,\frac{2\hat{\Gamma}_{ij}(p^2)\hat{\Gamma}_{jk}(p^2)\hat{\Gamma}_{ki}(p^2) - \hat{\Gamma}^2_{ki}(p^2)\hat{\Gamma}_{jj}(p^2) - \hat{\Gamma}^2_{ij}(p^2)\hat{\Gamma}_{kk}(p^2)}{\hat{\Gamma}_{jj}(p^2)\hat{\Gamma}_{kk}(p^2) - \hat{\Gamma}^2_{jk}(p^2)}$$

Complex pole $\mathcal{M}^2$ of each propagator is determined from

$$\mathcal{M}_i^2 - m_i^2 + \hat{\Sigma}^{\rm eff}_{ii}(\mathcal{M}_i^2) = 0,$$

where

$$\mathcal{M}^2 = M^2 - iM\Gamma,$$

Expansion around the real part of the complex pole:

$$\hat{\Sigma}_{jk}(\mathcal{M}^2_{h_a}) \approx \hat{\Sigma}_{jk}(M^2_{h_a}) + i\,{\rm Im}\left[\mathcal{M}^2_{h_a}\right]\hat{\Sigma}'_{jk}(M^2_{h_a})$$

$j, k = h, H, A,\ a = 1, 2, 3$

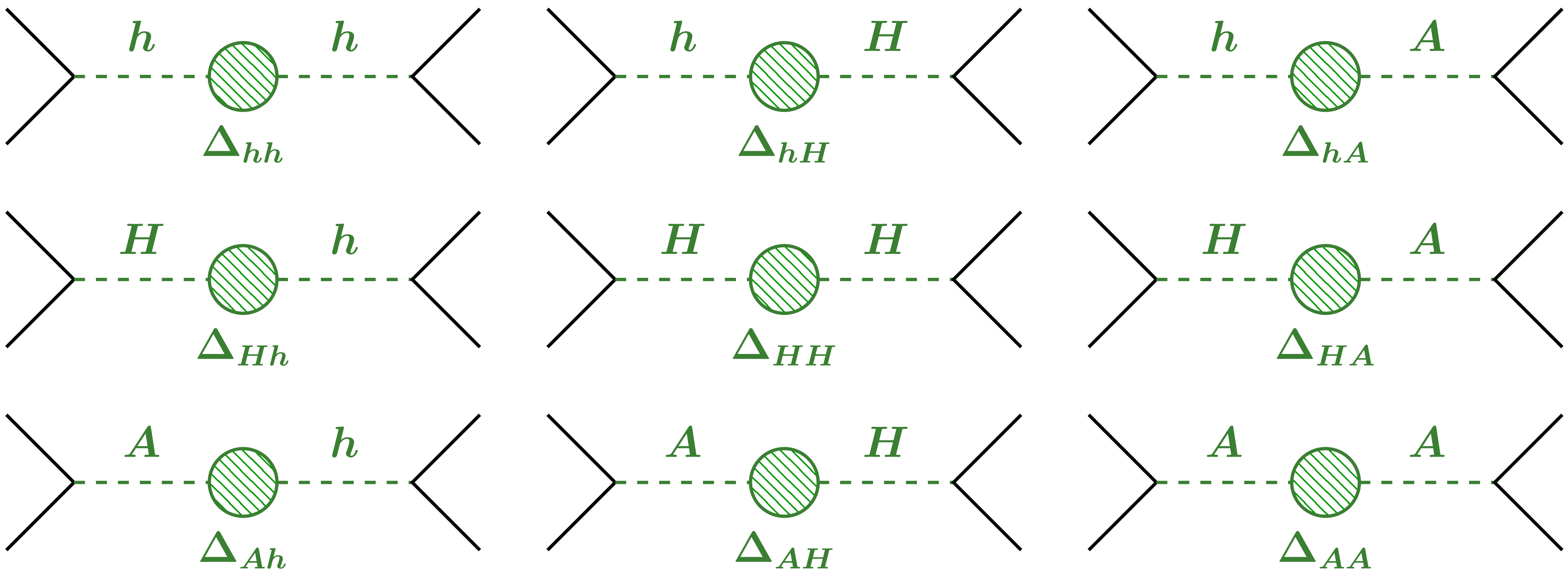
Propagator matrix

[E. Fuchs, G. W. '16]

$$\boldsymbol{\Delta}_{hHA} = \begin{pmatrix} \Delta_{hh} & \Delta_{hH} & \Delta_{hA} \\ \Delta_{Hh} & \Delta_{HH} & \Delta_{HA} \\ \Delta_{Ah} & \Delta_{AH} & \Delta_{AA} \end{pmatrix}$$

Without mixing: Δ_{hh}, … has a single pole

For (n x n) mixing: each of the entries Δ_{hh}, … in general has n poles



Finite wave function normalisation factors for amplitudes with external Higgs bosons

Finite wave-function normalisation factors ensure the correct on-shell properties of the S matrix

$$Z_h = \frac{1}{\frac{\partial}{\partial p^2}\left(\frac{i}{\Delta_{hh}(p^2)}\right)\Big|_{p^2=\mathcal{M}^2_{h_a}}} \qquad Z_H = \frac{1}{\frac{\partial}{\partial p^2}\left(\frac{i}{\Delta_{HH}(p^2)}\right)\Big|_{p^2=\mathcal{M}^2_{h_b}}}$$

$$Z_A = \frac{1}{\frac{\partial}{\partial p^2}\left(\frac{i}{\Delta_{AA}(p^2)}\right)\Big|_{p^2=\mathcal{M}^2_{h_c}}}$$

Complex quantities, evaluated at complex pole

$$Z_{hH} = \frac{\Delta_{hH}}{\Delta_{hh}}\Big|_{p^2=\mathcal{M}^2_{h_a}} \qquad Z_{Hh} = \frac{\Delta_{hH}}{\Delta_{HH}}\Big|_{p^2=\mathcal{M}^2_{h_b}} \qquad Z_{Ah} = \frac{\Delta_{hA}}{\Delta_{AA}}\Big|_{p^2=\mathcal{M}^2_{h_c}}$$

$$Z_{hA} = \frac{\Delta_{hA}}{\Delta_{hh}}\Big|_{p^2=\mathcal{M}^2_{h_a}} \qquad Z_{HA} = \frac{\Delta_{HA}}{\Delta_{HH}}\Big|_{p^2=\mathcal{M}^2_{h_b}} \qquad Z_{AH} = \frac{\Delta_{HA}}{\Delta_{AA}}\Big|_{p^2=\mathcal{M}^2_{h_c}}$$

Finite wave function normalisation factors for amplitudes with external Higgs bosons

WF constants can be written as (non-unitary) matrix $\hat{\mathrm{Z}}$,

$$\hat{\mathbf{Z}} = \begin{pmatrix} \sqrt{Z_h} & \sqrt{Z_h} Z_{hH} & \sqrt{Z_h} Z_{hA} \\ \sqrt{Z_H} Z_{Hh} & \sqrt{Z_H} & \sqrt{Z_H} Z_{HA} \\ \sqrt{Z_A} Z_{Ah} & \sqrt{Z_A} Z_{AH} & \sqrt{Z_A} \end{pmatrix}, \qquad \begin{pmatrix} \hat{\Gamma}_{h_a} \\ \hat{\Gamma}_{h_b} \\ \hat{\Gamma}_{h_c} \end{pmatrix} = \hat{\mathbf{Z}} \cdot \begin{pmatrix} \hat{\Gamma}_h \\ \hat{\Gamma}_H \\ \hat{\Gamma}_A \end{pmatrix}$$

Fulfills the conditions

Every assignment between *h*a, *h*b, *h*c, and *h*, *H*, *A* is possible!

Unit residues

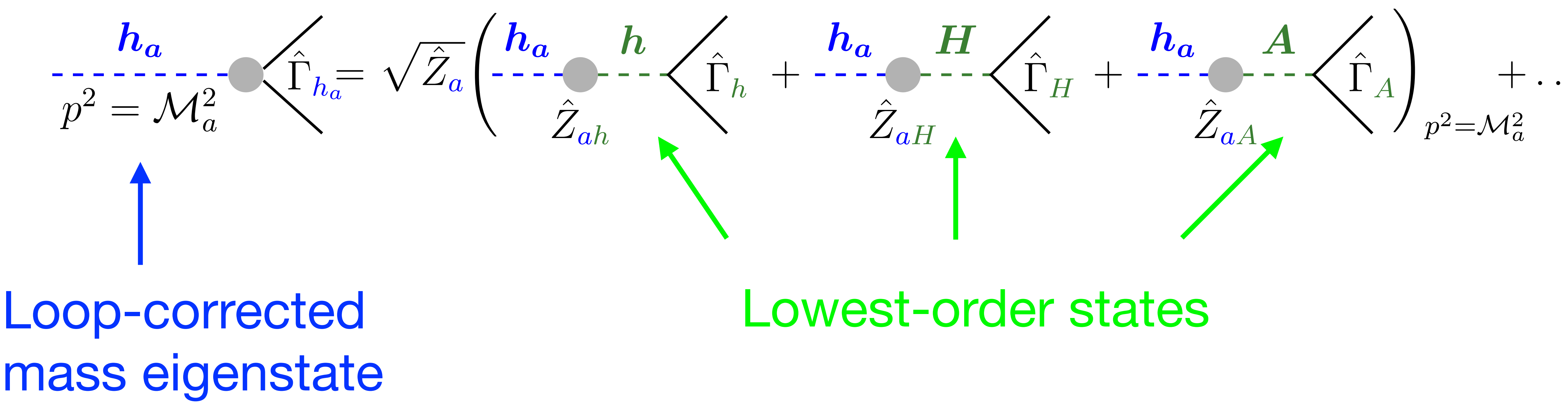
Off-diagonal contributions vanish on-shell

$$\lim_{p^2 \to \mathcal{M}^2_{h_a}} -\frac{i}{p^2 - \mathcal{M}^2_{h_a}} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{hh} = 1$$

$$\lim_{p^2 \to \mathcal{M}^2_{h_b}} -\frac{i}{p^2 - \mathcal{M}^2_{h_b}} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{HH} = 1$$

$$\lim_{p^2 \to \mathcal{M}^2_{h_c}} -\frac{i}{p^2 - \mathcal{M}^2_{h_c}} \left(\hat{\mathbf{Z}} \cdot \hat{\mathbf{\Gamma}}_2 \cdot \hat{\mathbf{Z}}^T \right)_{AA} = 1$$

Finite wave function normalisation factors for amplitudes with external Higgs bosons



⇒ Mixing effects taken into account (via non-unitary matrix)

Correct normalisation of the S matrix

Application of wave function normalisation factors for internal particles: "generalised narrow-width approx."

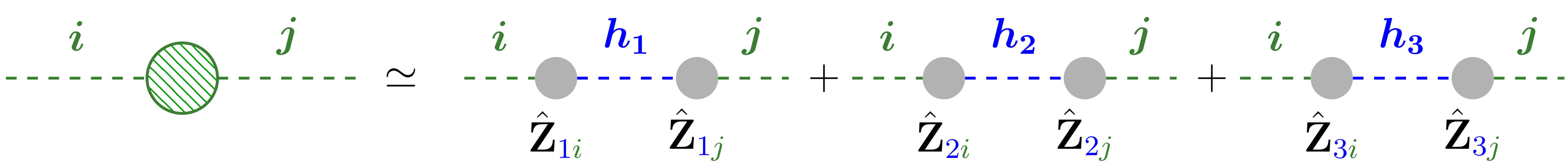
[E. Fuchs, G. W. '16]

Expansion of the full propagator around a complex pole: dominant contribution from Breit-Wigner factor,

$$\Delta_a^{\mathrm{BW}}(p^2) := \frac{i}{p^2 - \mathcal{M}_a^2} = \frac{i}{p^2 - M_{h_a}^2 + i M_{h_a} \Gamma_{h_a}}$$

times wave function normalisation factors:

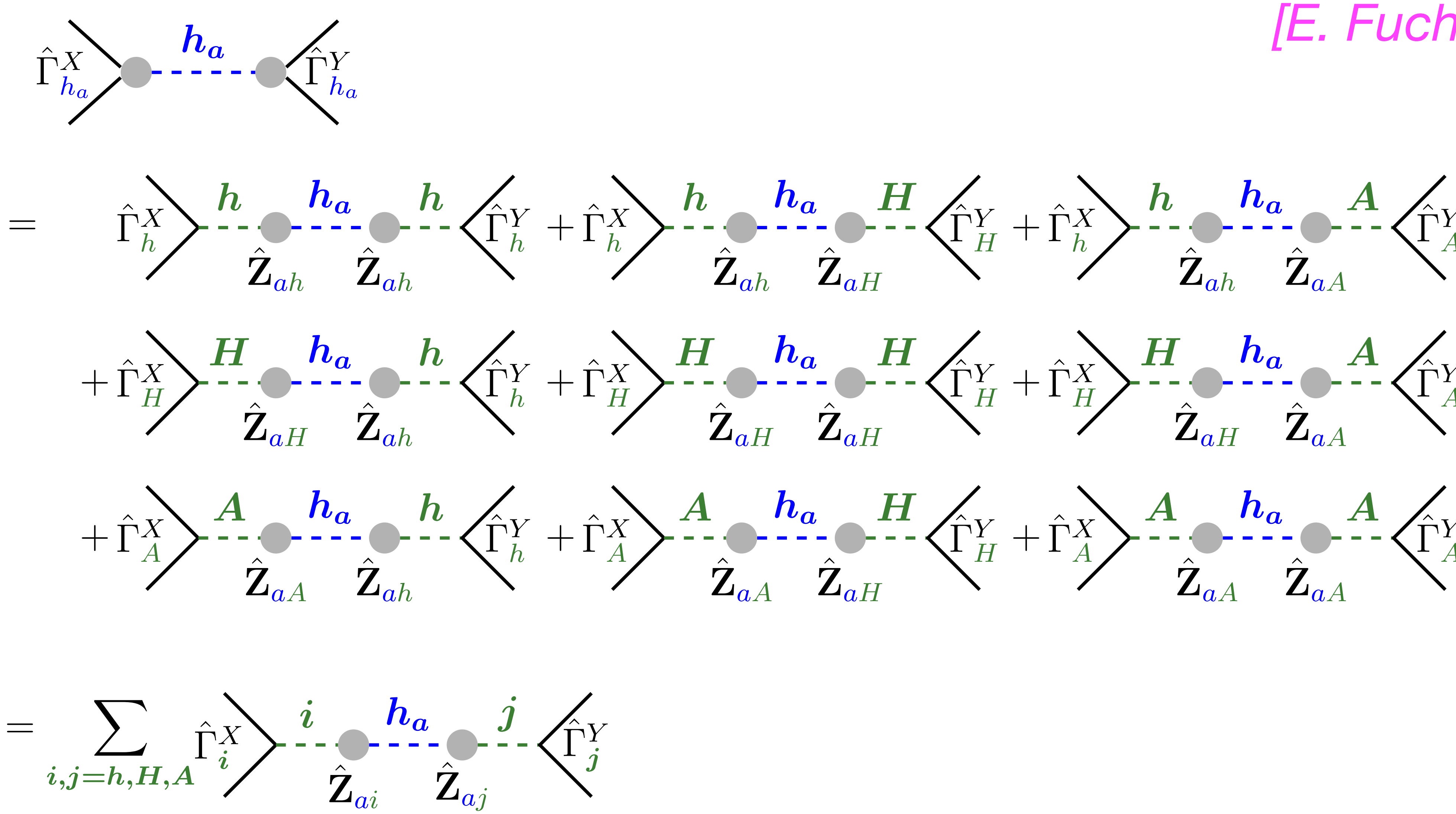
$$\Delta_{ij}(p^2) \simeq \sum_{a=1}^{3} \hat{\mathbf{Z}}_{ai}\, \Delta_a^{\mathrm{BW}}(p^2)\, \hat{\mathbf{Z}}_{aj}$$



⇒ Approximation of the full off-shell propagator matrix in terms of the on-shell contributions of all complex poles

Application of the propagator approximation

[E. Fuchs, G. W. ’16]



⇒ Expression of the full process in terms of the on-shell production and decay of the intermediate states (⟶ generalised narrow-width approximation)

⇒ Convenient incorporation of higher-order contributions, mixing and interference effects

Propagator approximation vs. full result

[E. Fuchs, G. W. '16]

Without interference contribution

Individual contribution

Propagator approximation

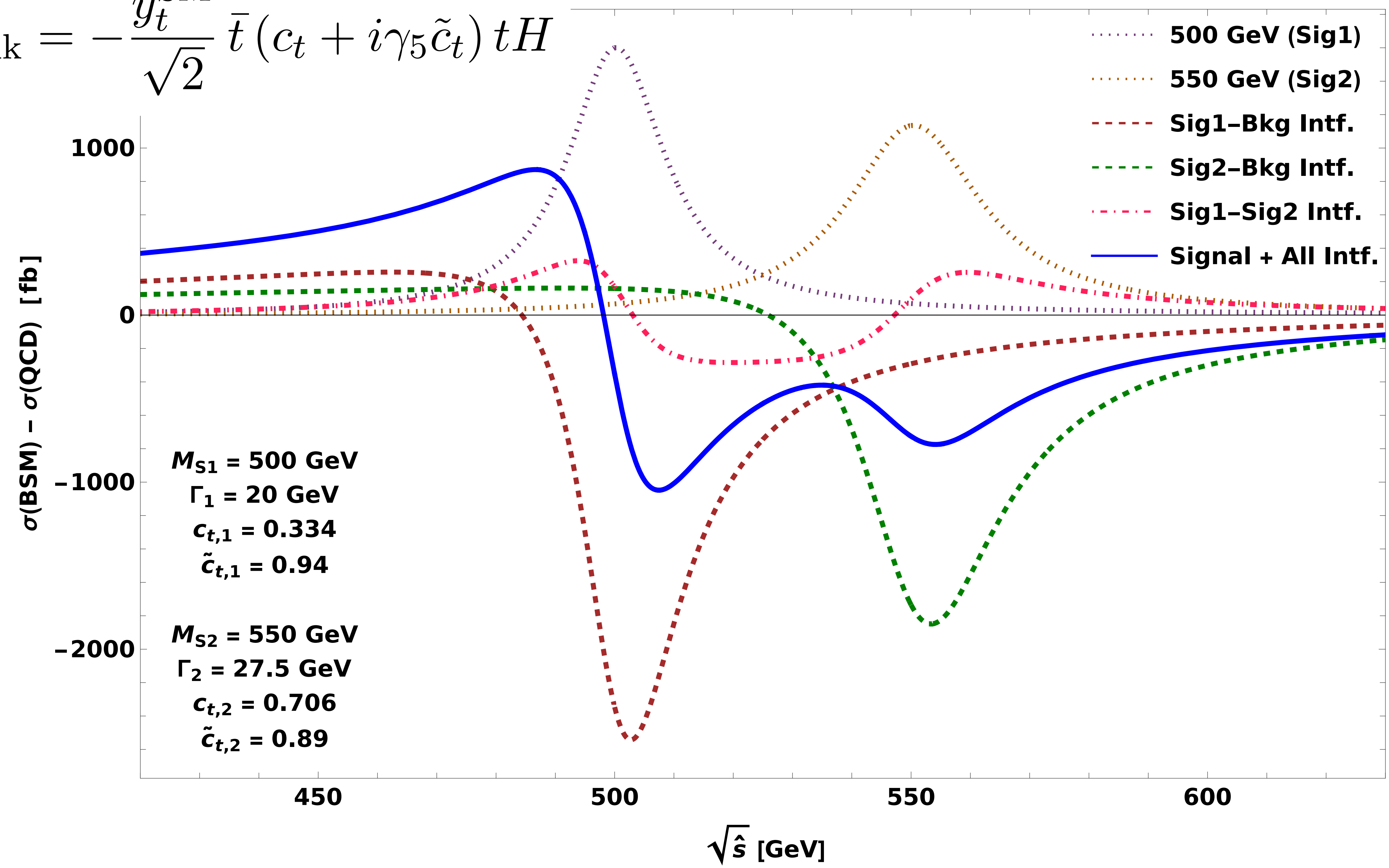
Full result

⇒ Very good agreement of propagator approximation with full result
Incorporation of interference effects is crucial

Analysis of BSM Higgs searches in the tt final state: parton-level analysis (CPV effective couplings)

[H. Bahl, R. Kumar, G. W. '22]

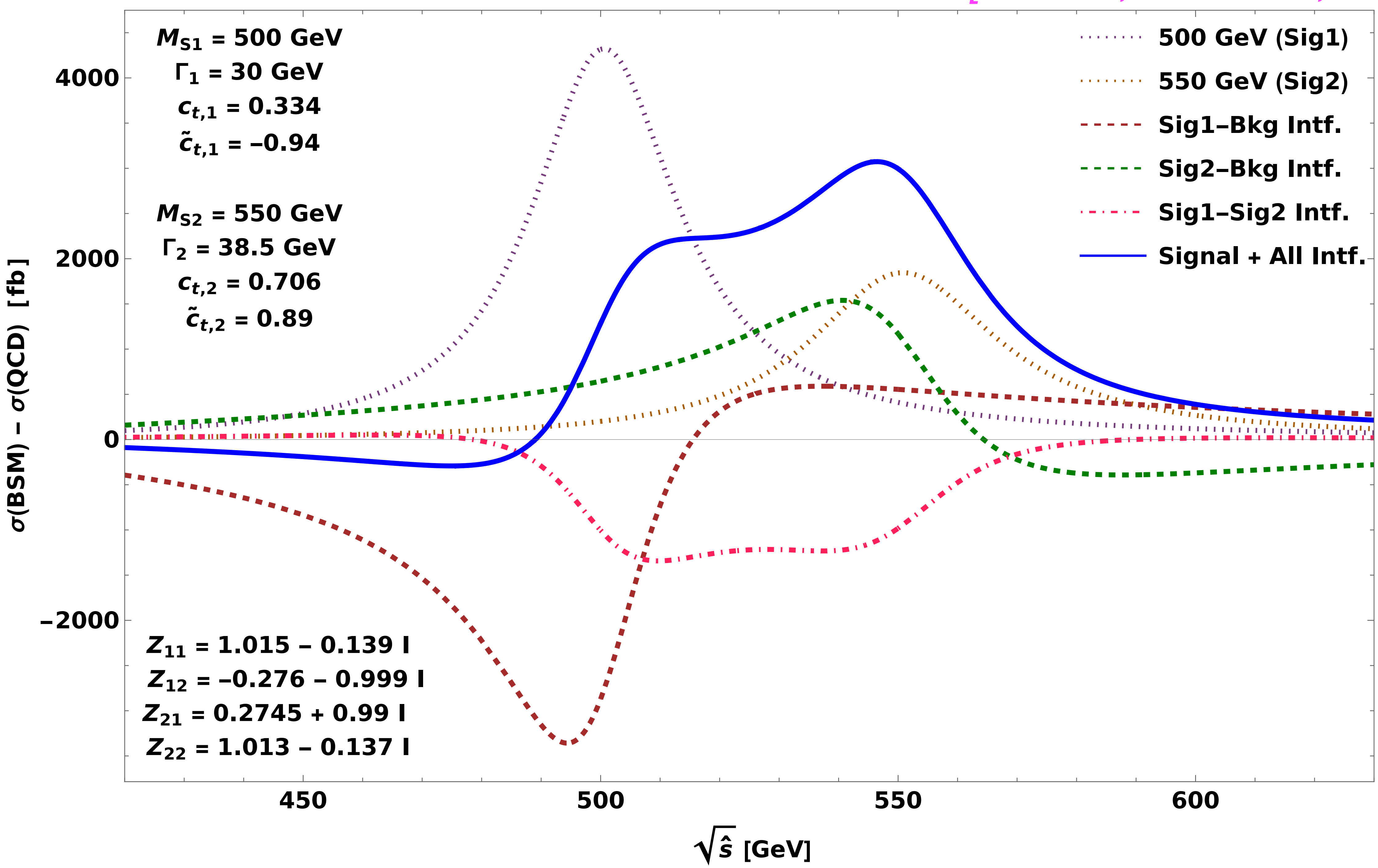
$$\mathcal{L}_{\text{yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}}\,\bar{t}\,(c_t + i\gamma_5\tilde{c}_t)\,tH$$



⇒ Interference effects have large impact on the shape of the distribution

Analysis of BSM Higgs searches in the tt final state: parton-level analysis (Z-factors included)

[H. Bahl, R. Kumar, G. W. '22]

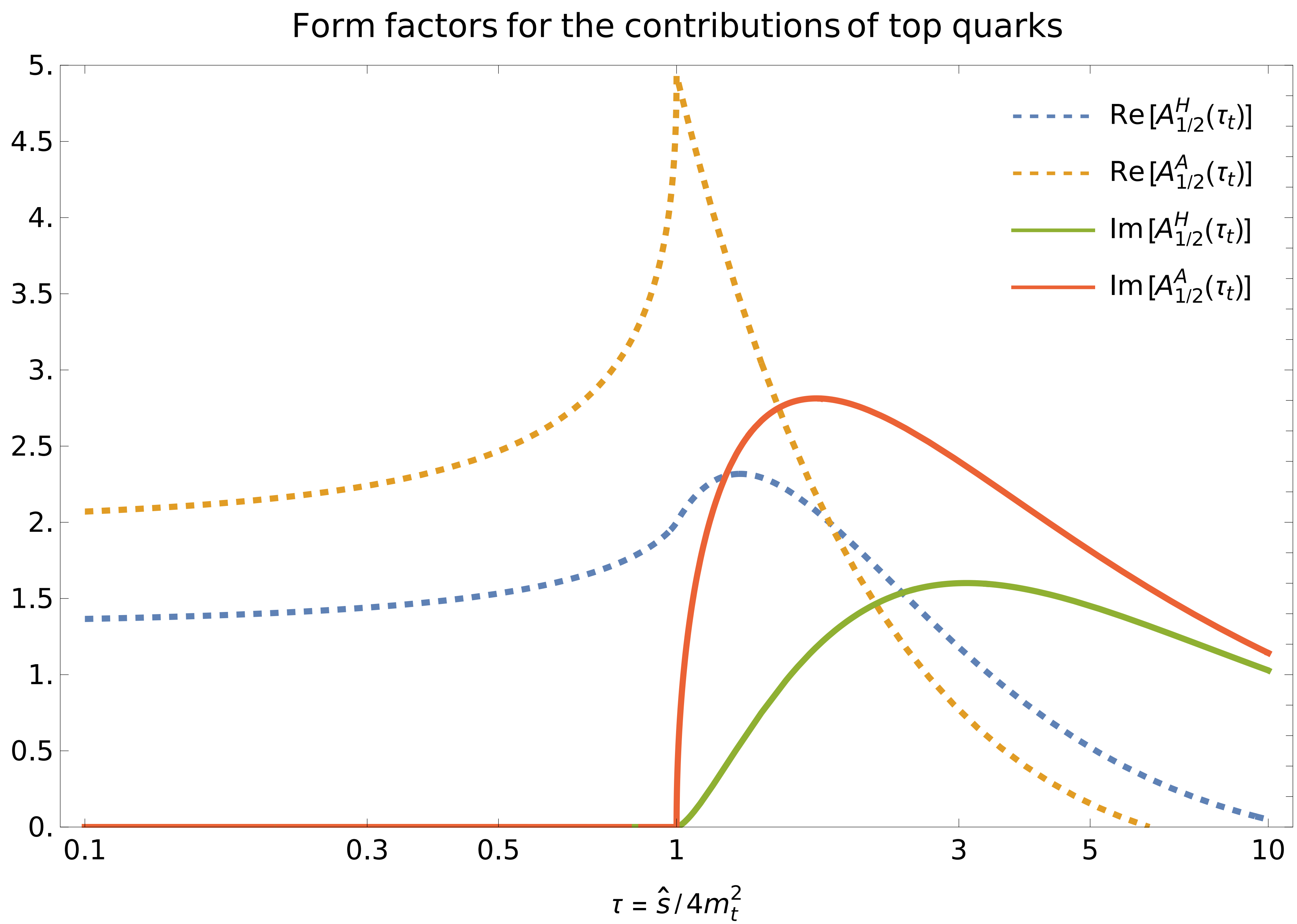


⇒ Wave function normalisation factors have large effects

Analysis of BSM Higgs searches in the tt final state: Monte Carlo implementation (*MADGRAPH*)

[H. Bahl, R. Kumar, G. W. '22]

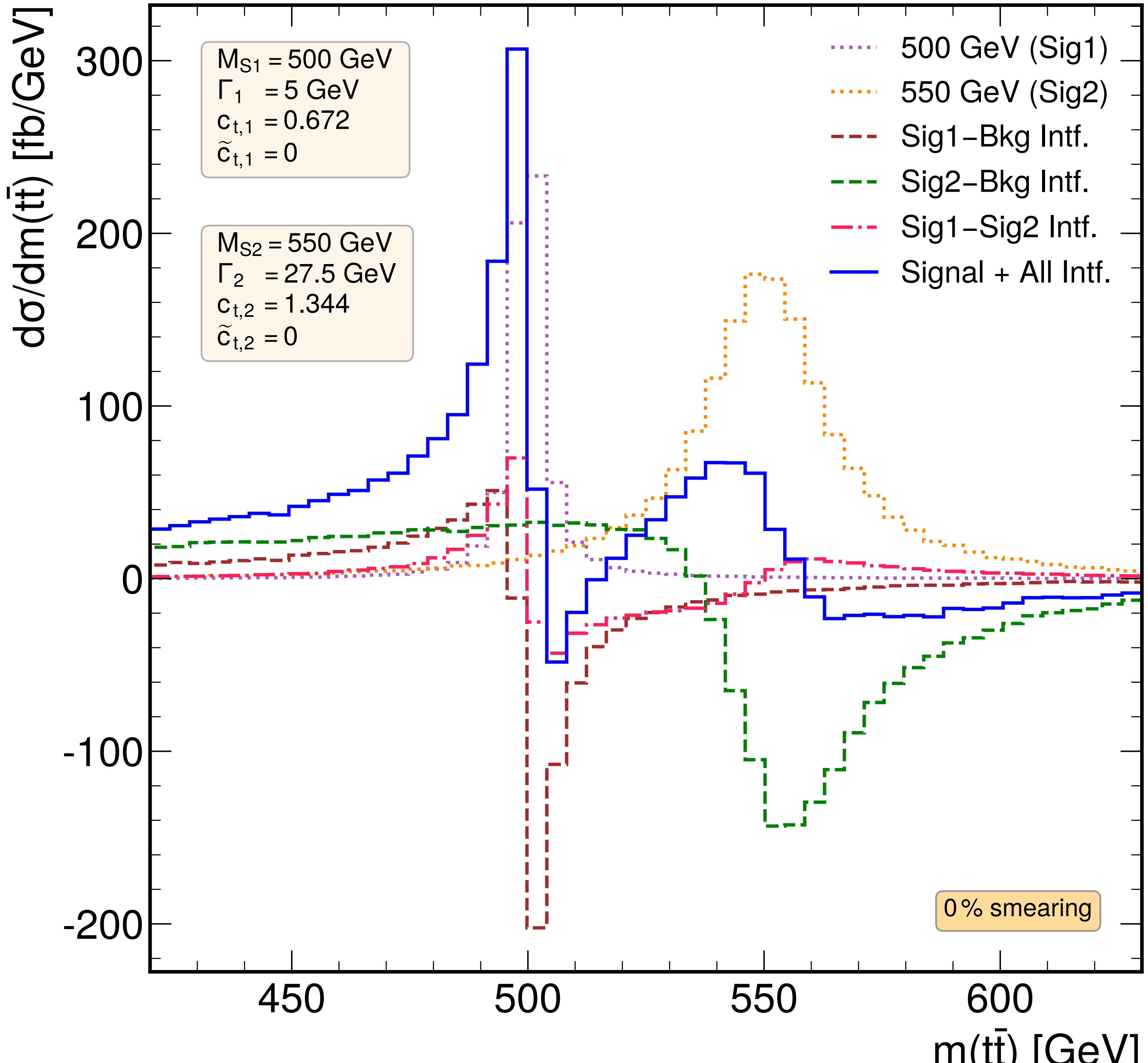
Loop function for gluon-fusion Higgs production:



⇒ Crucial to take into account finite top-mass effects; imaginary part of the form factor is very important for interference contribution!

Analysis of BSM Higgs searches in the tt final state: Monte Carlo implementation (*MADGRAPH*)

[H. Bahl, R. Kumar, G. W. '22]

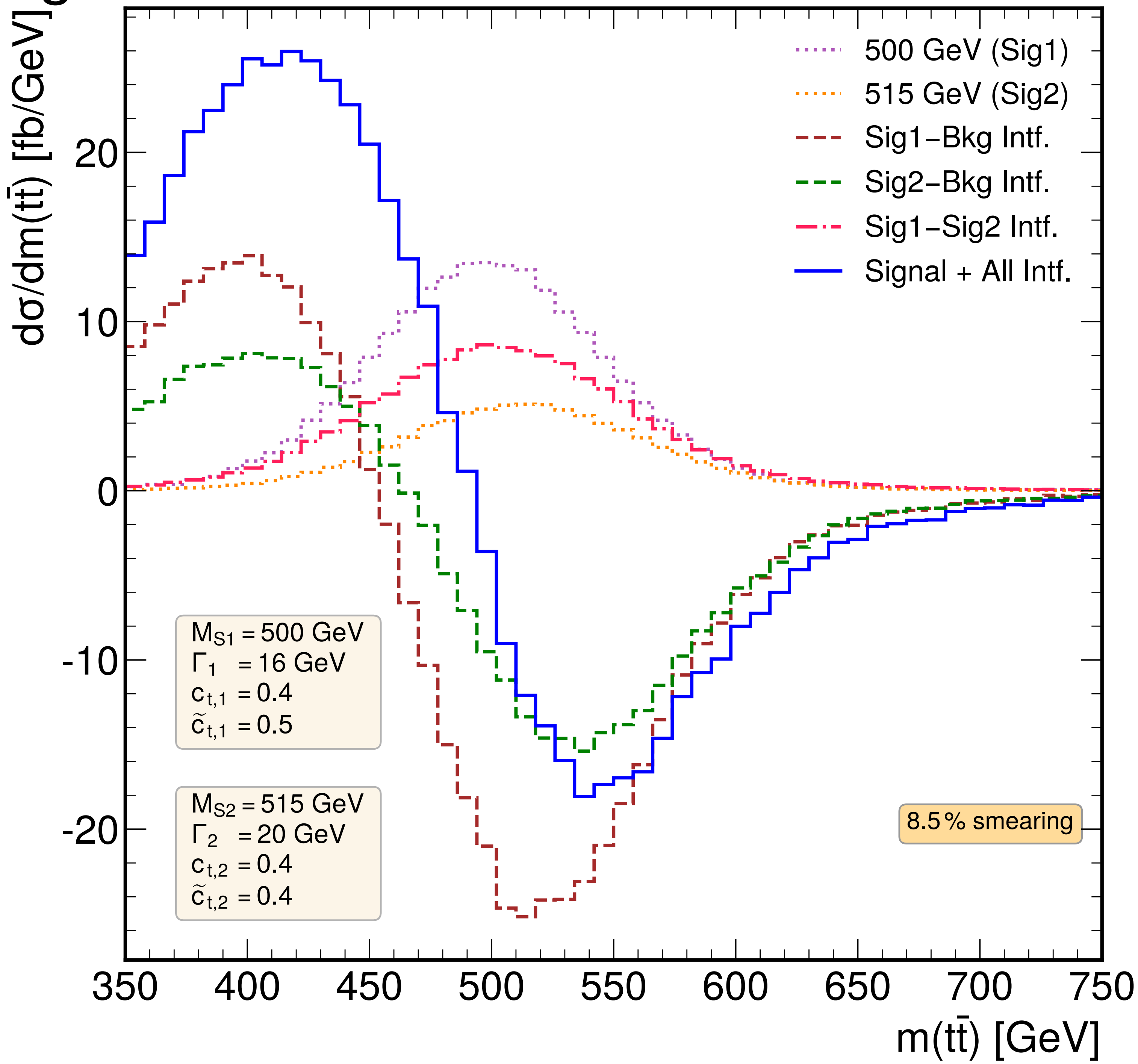


⇒ Interference effects have large impact on the shape of the distribution

Monte Carlo implementation (*MADGRAPH*): impact of "effective" experimental smearing

[H. Bahl, R. Kumar, G. W. '22]

8.5% smearing:

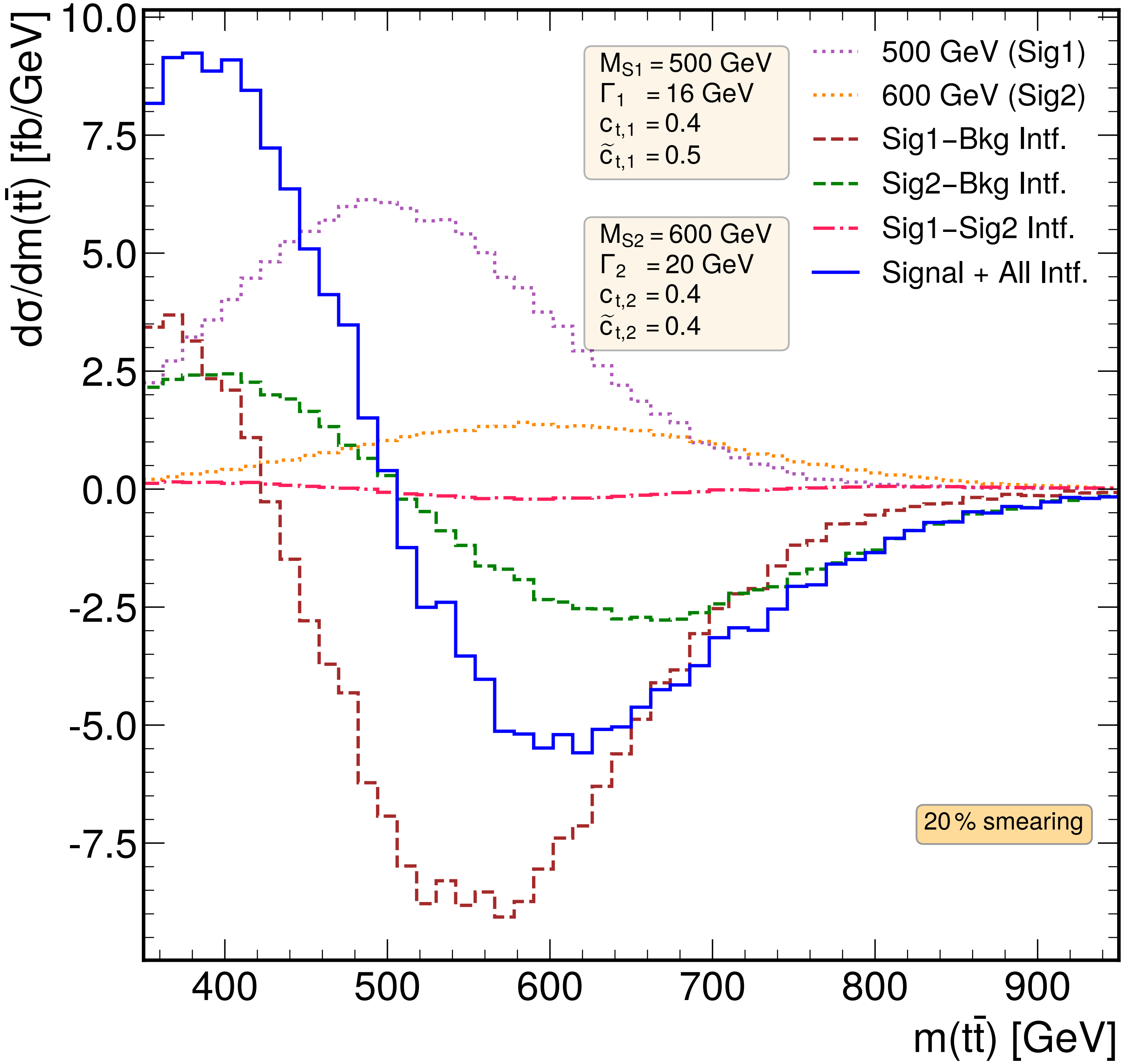


⇒ Measurements may be able to resolve a peak-dip like structure

Monte Carlo implementation (*MADGRAPH*): impact of "effective" experimental smearing

[H. Bahl, R. Kumar, G. W. '22]

20% smearing:

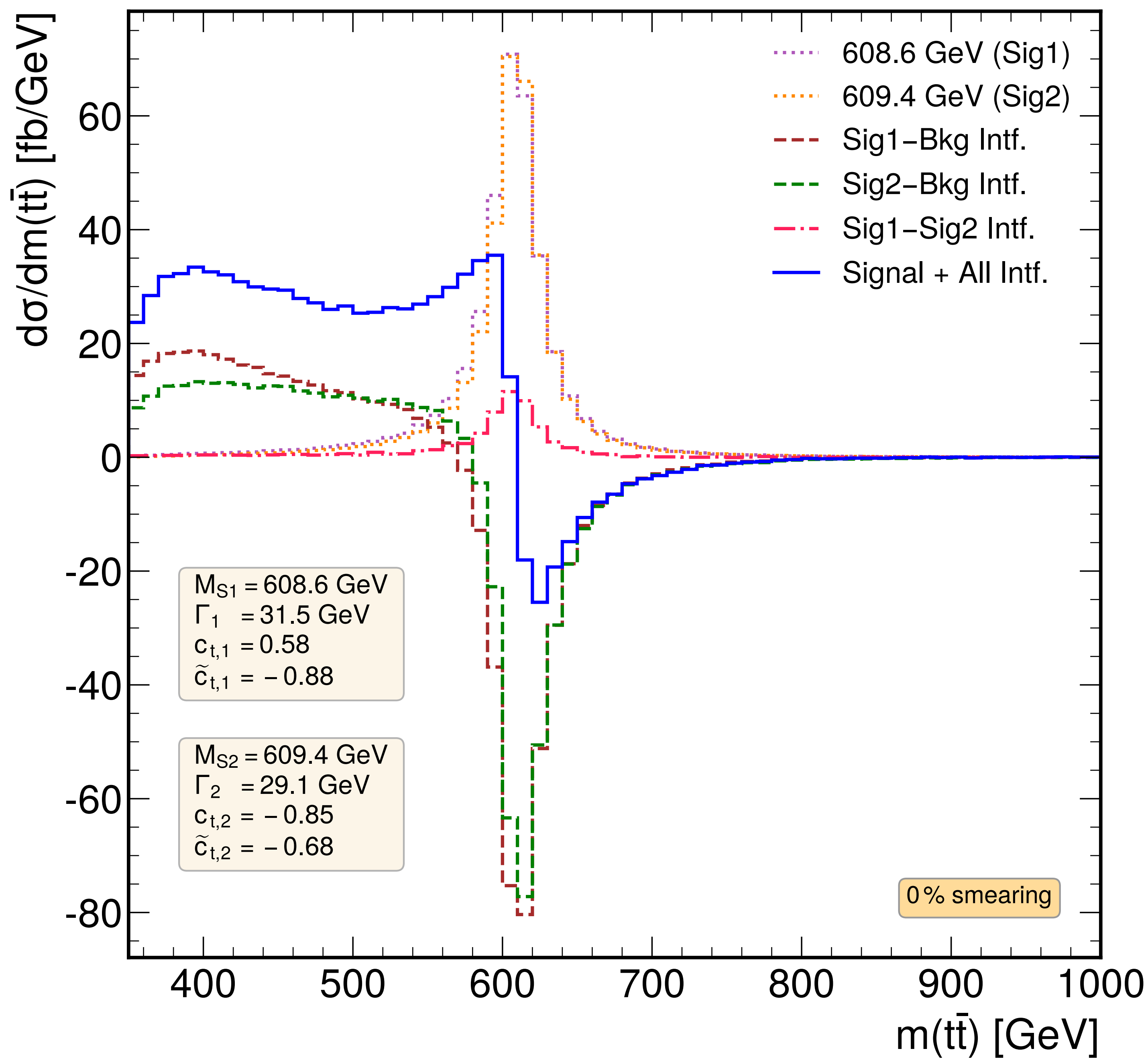


⇒ Measurements may be able to resolve a peak-dip like structure resolution of the two BSM Higgs bosons may be difficult

Application to the C2HDM and comparison with existing results in the literature

[H. Bahl, R. Kumar, G. W. '22]

Comparison with results of *[P. Basler et al. '20]*



⇒ Good agreement with previous results, but signal-signal interference contributions (not considered there) may be sizeable

Conclusions

Higgs phenomenology in extended Higgs sectors: careful treatment of unstable particles, mixing, interferences necessary

Typical situation: a light SM-like Higgs boson + heavy Higgs bosons that are nearly mass-degenerate (note: additional Higgs bosons can also be lighter than the state at 125 GeV)

Mixing between the heavy Higgs bosons can lead to large interference effects, resonance-type behaviour

Signal-background interferences (for different BSM Higgs bosons) + signal-signal interferences can modify distributions very significantly compared to the case of a single BSM Higgs resonance!

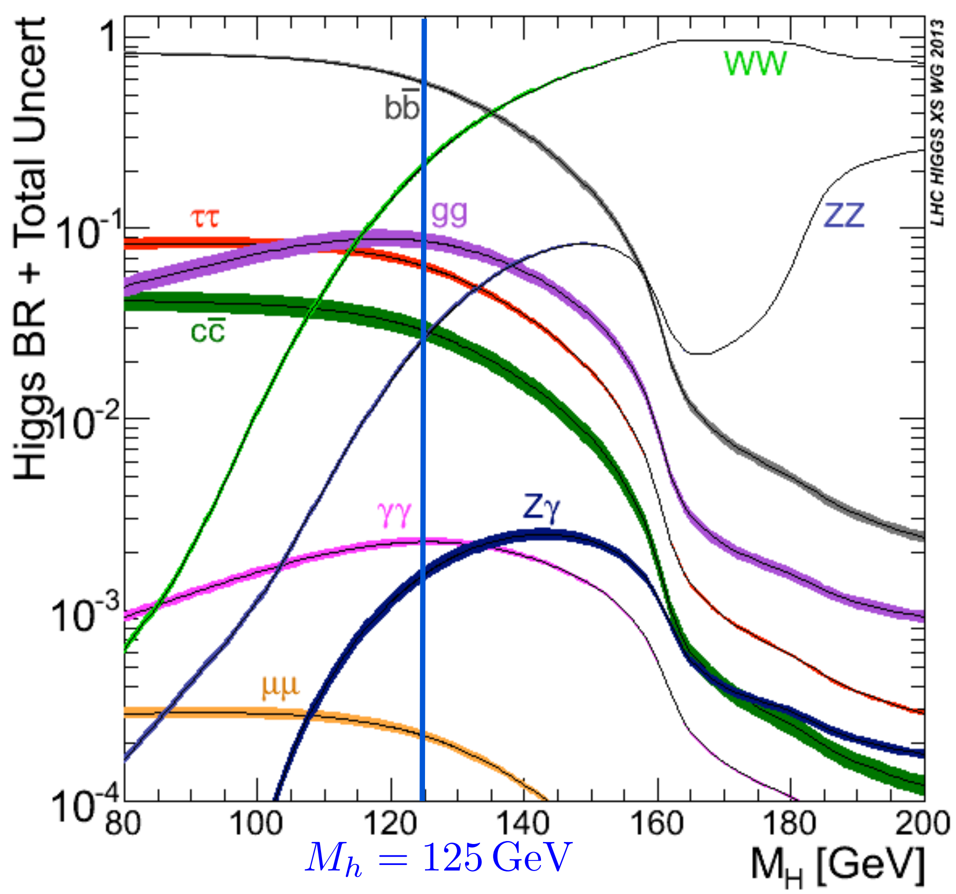
Detailed studies are in progress

Backup

Mass dependence and off-shell effects

High sensitivity on mass value and importance of off-shell effects for BR(H → ZZ*), BR(H → WW*) have same physical origin:

SM Higgs branching fractions:



[LHC Higgs XS WG ’14]

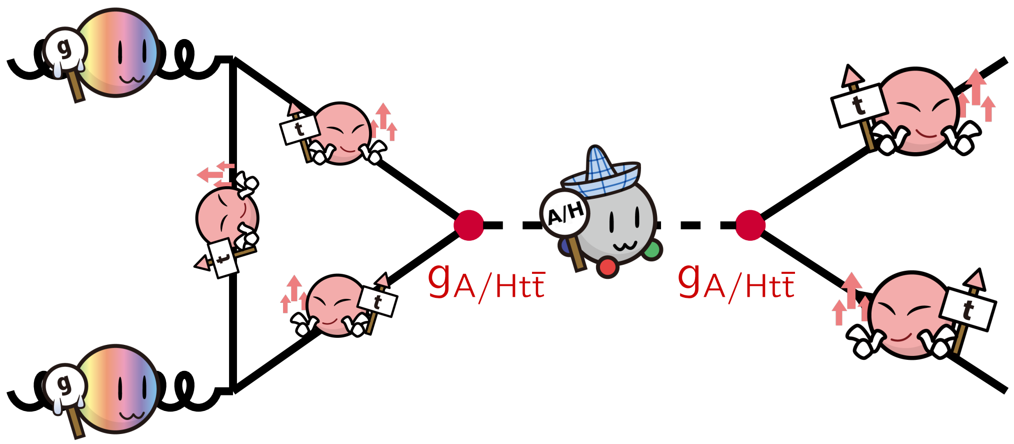
For a 125 GeV Higgs boson the branching ratios into BR(H → ZZ*), BR(H → WW*) are far below threshold

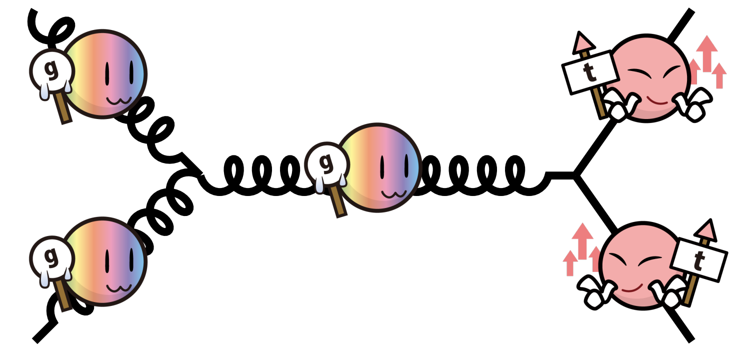
⇒ Strong phase-space suppression, steep rise with M_H

⇒ Sensitive dependence on M_H, off-shell effects are important

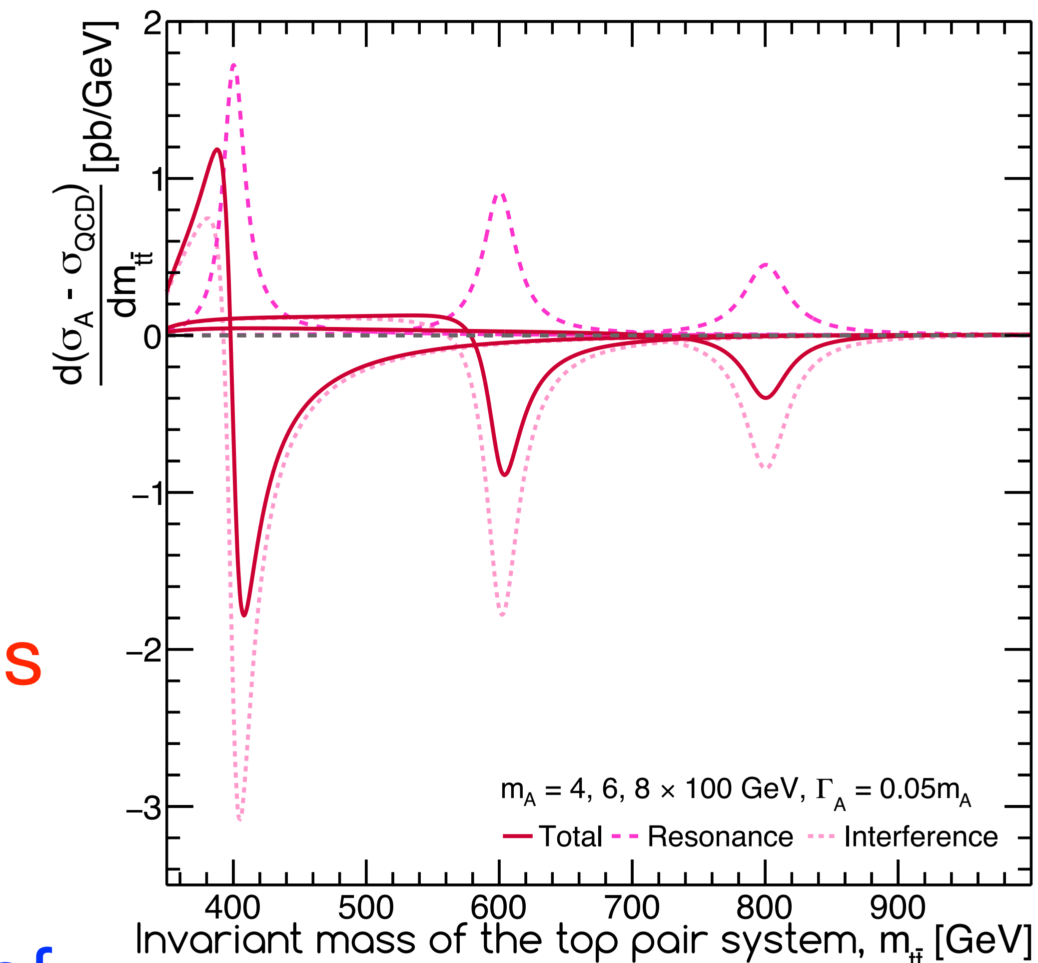
CMS: excess in search for A → tt at about 400 GeV

[A. Anuar ’21]





Interference ⇒



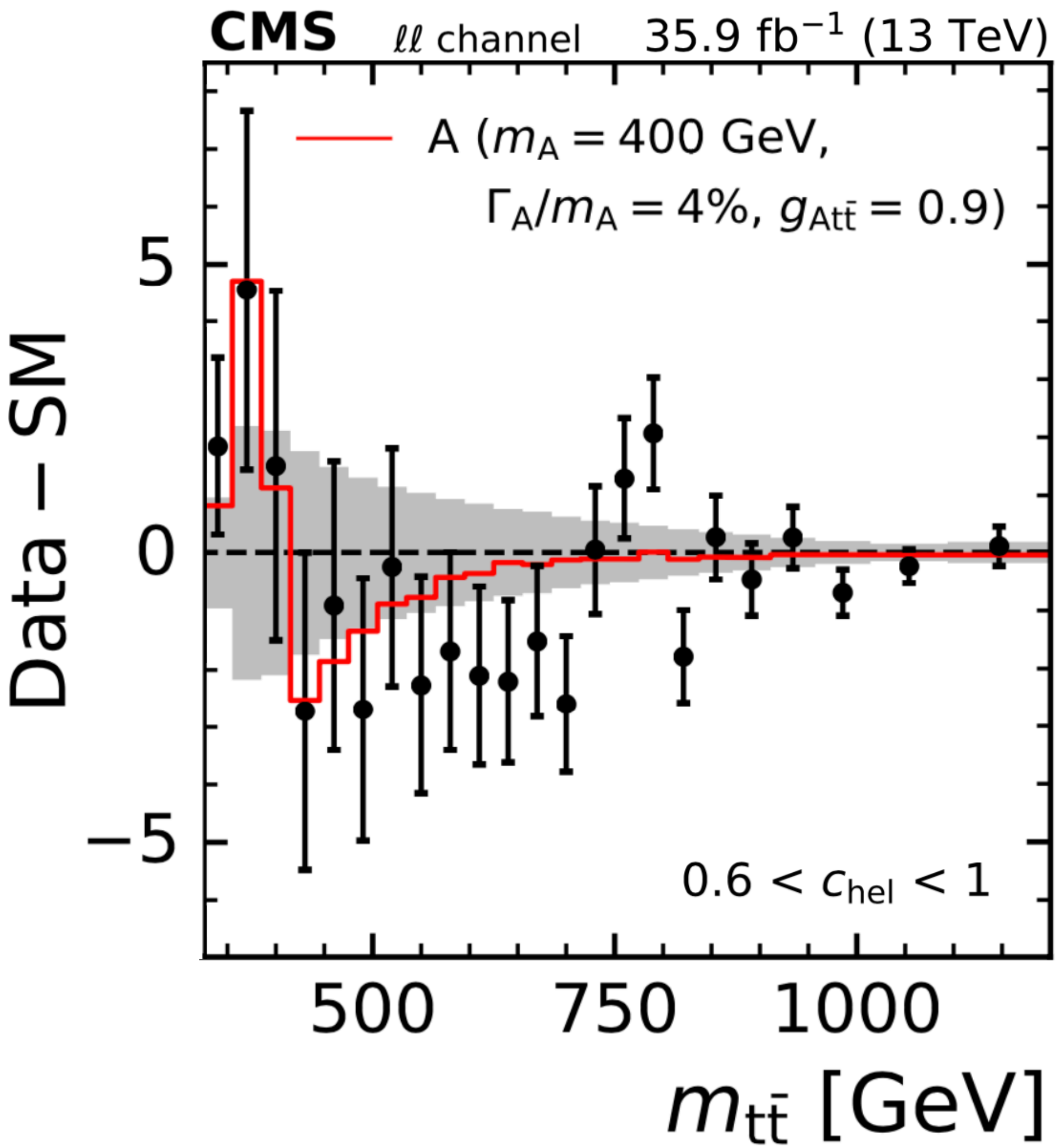
Signal-background interference yields peak-dip structure

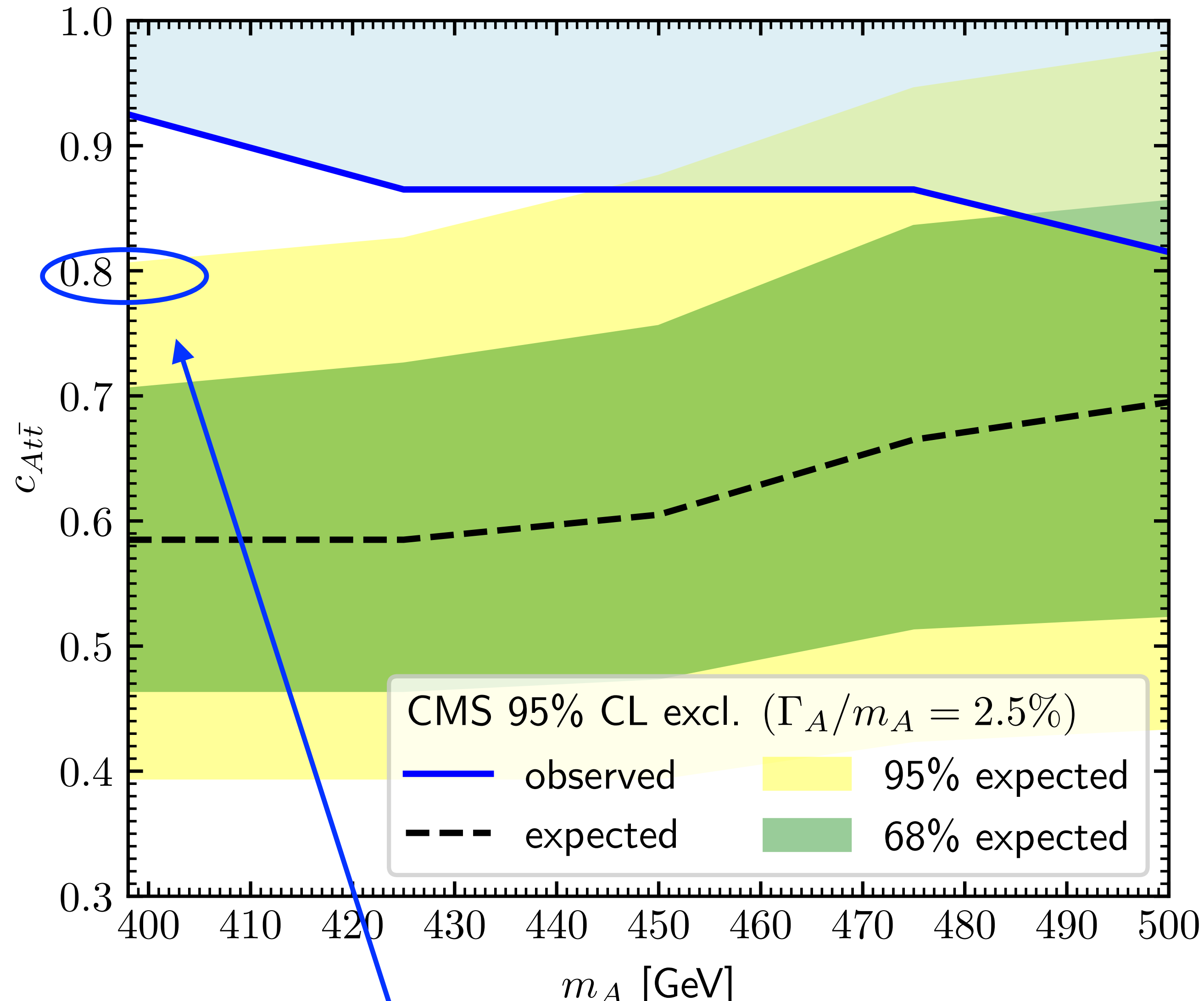
Analysed using angular correlations of the top and anti-top decay products

Search for additional Higgs bosons: H, A → tt

Excess in CMS search at about 400 GeV:

[CMS Collaboration '19]



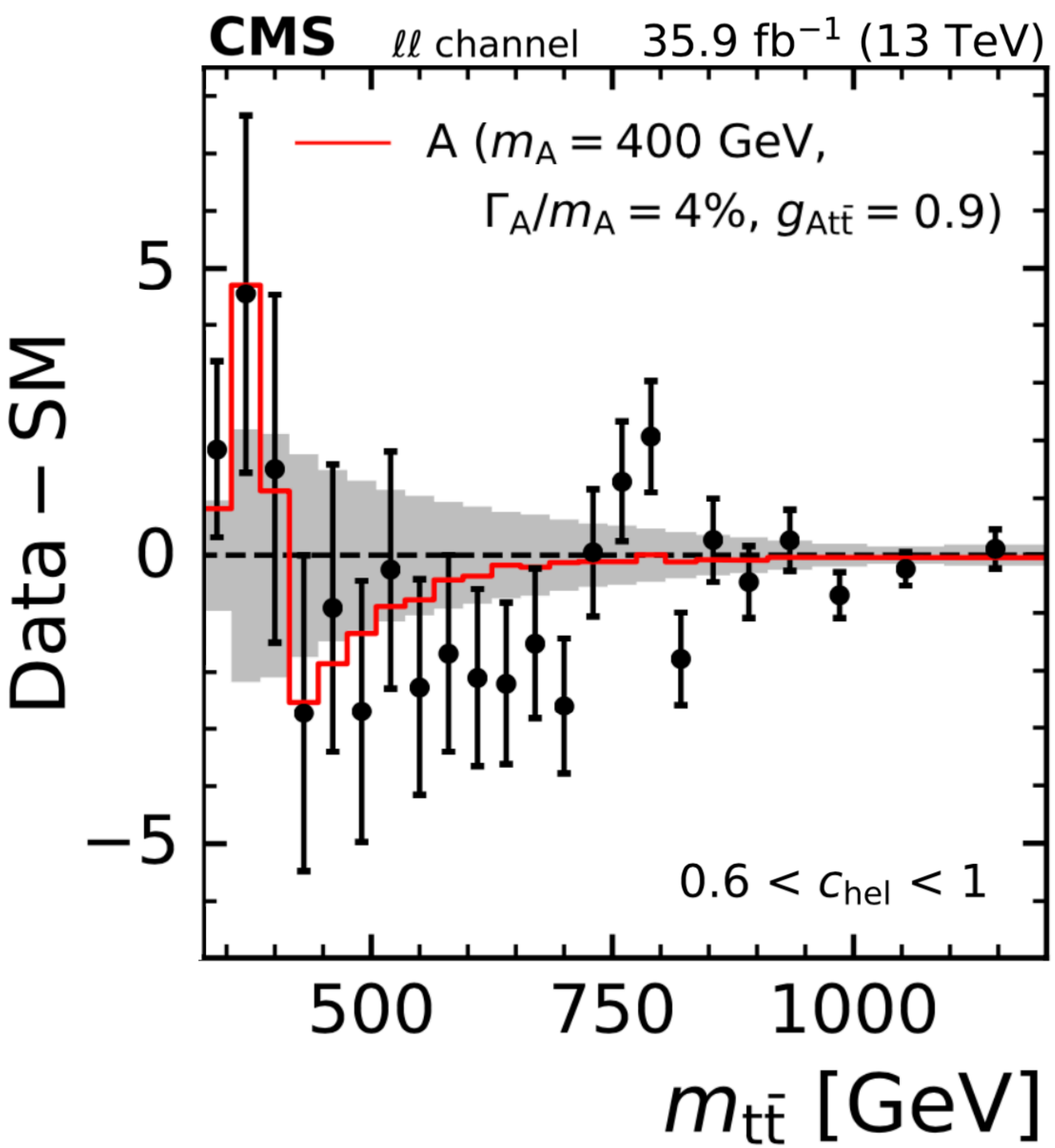


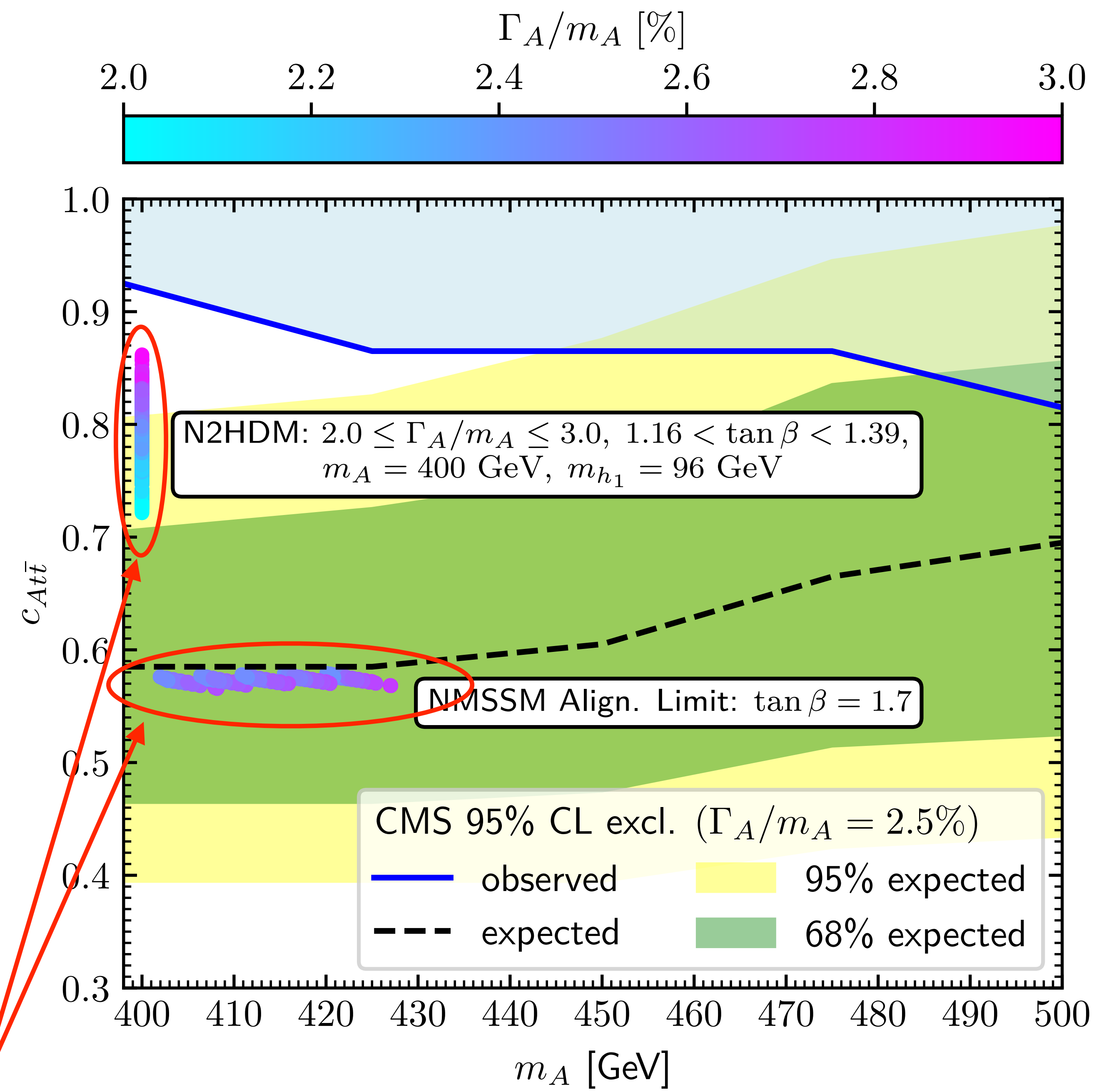
CMS, best fit value for Γ_A/m_A = 2.5%

Search for additional Higgs bosons: H, A → tt

[T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. W. '21]

Excess in CMS search at about 400 GeV:



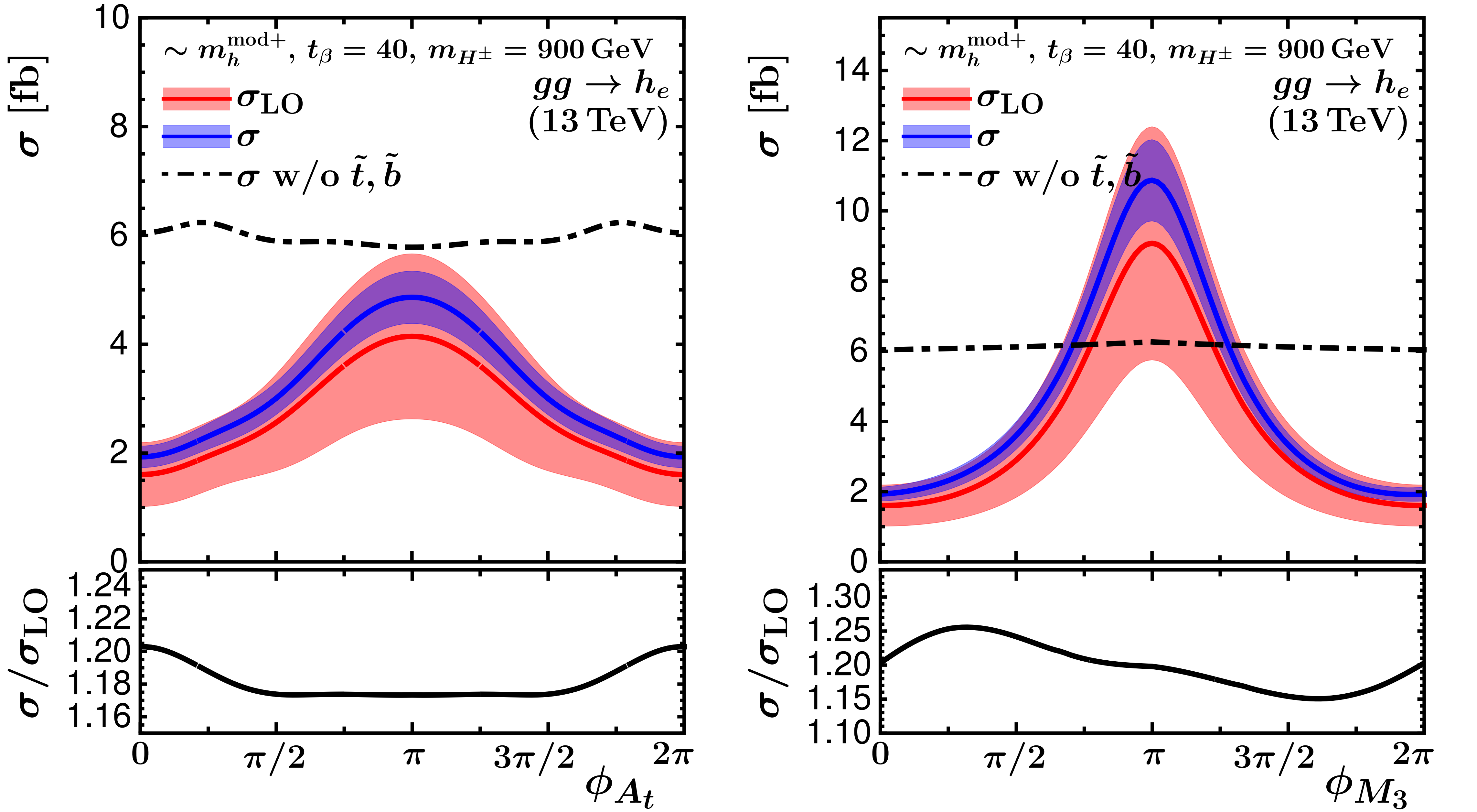


⇒ Good description of the A → tt excess at 400 GeV in models with extended Higgs sectors (N2HDM, NMSSM)

Higgs production via gluon fusion in the MSSM with CP-violation: *SusHiMi* code

[S. Liebler, S. Patel, G. W. '16]

Phase dependence for dominantly CP-even state "h_e":

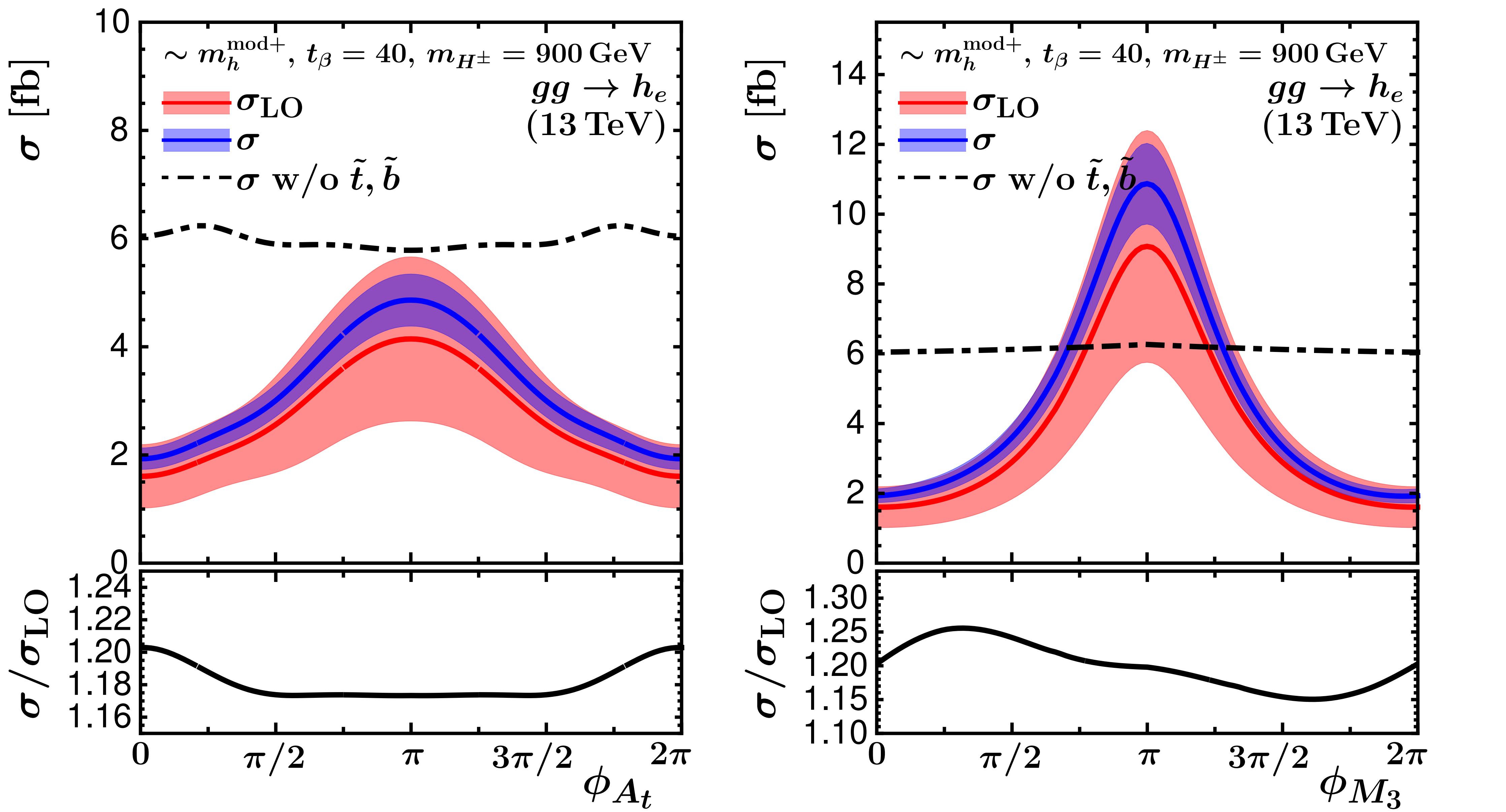


⇒ Significant reduction of theoretical uncertainty w.r.t. LO result

Higgs production via gluon fusion in the MSSM: incorporation of CP-violating effects

SusHiMi code: *[S. Liebler, S. Patel, G. Weiglein '16]*

gg → h_2 / h_3, phase dependence for dominantly CP-even state "h_e":

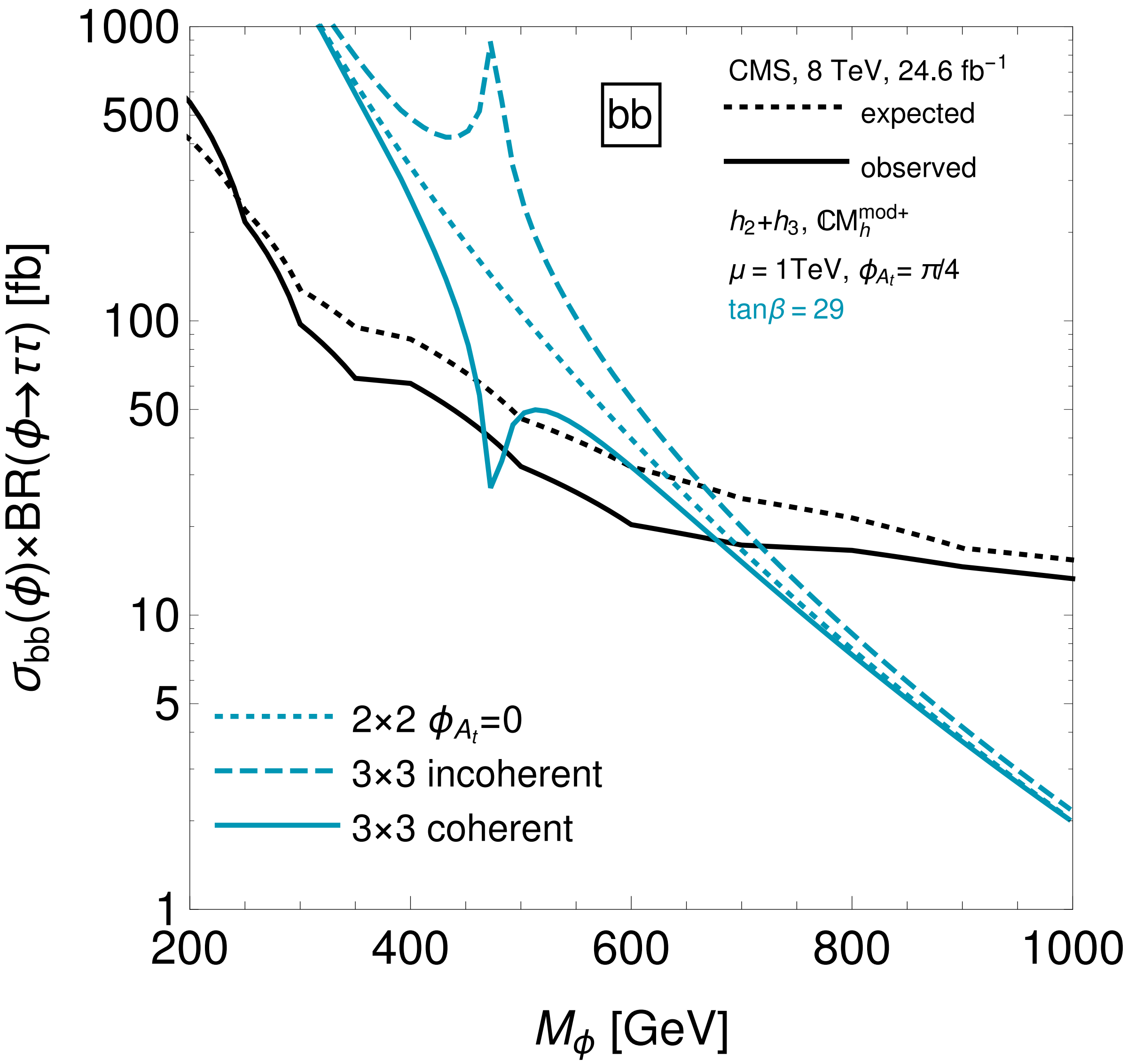


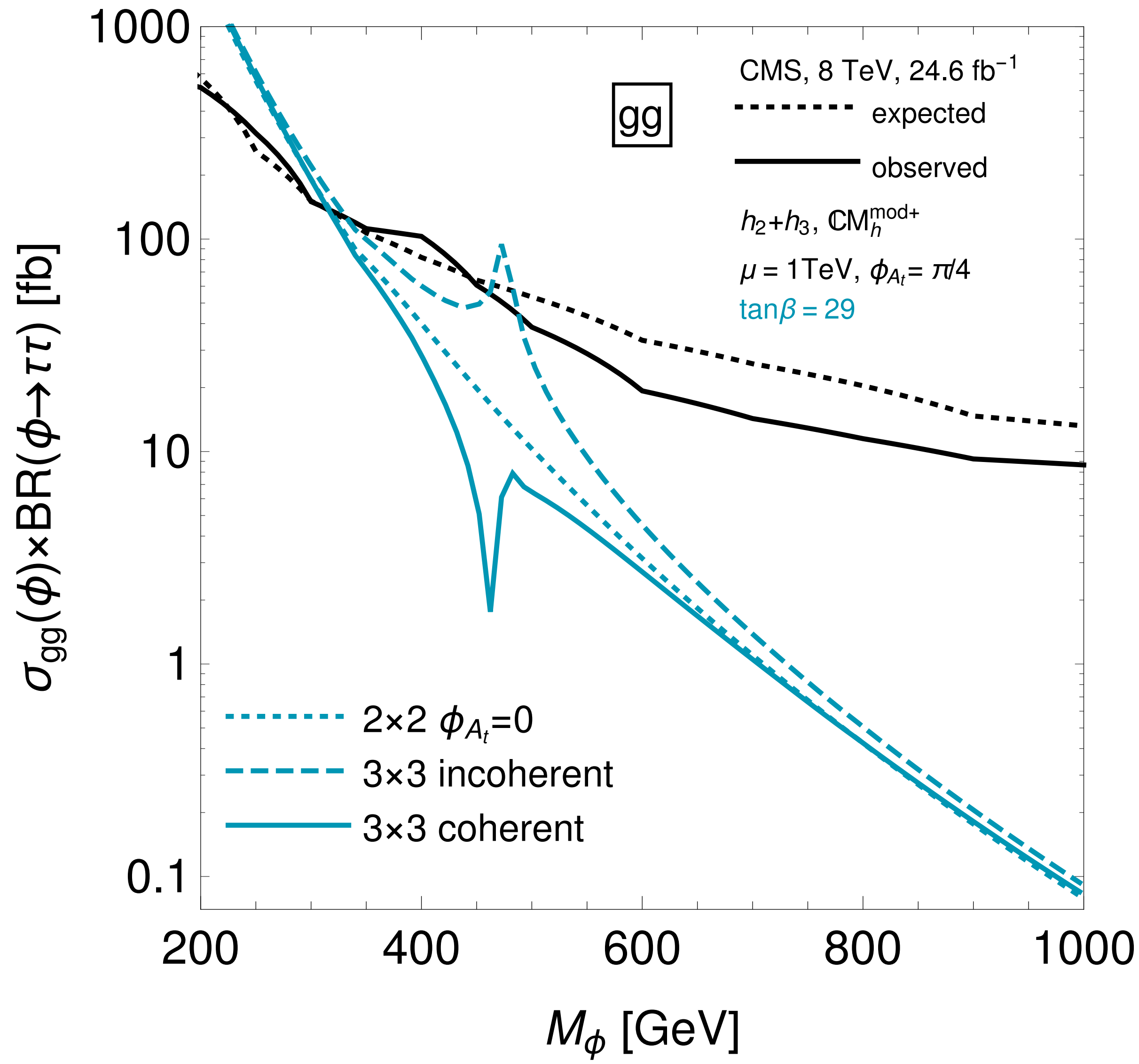
⇒ Significant reduction of theoretical uncertainty w.r.t. leading-order (LO) result

The interference between the two nearly mass-degenerate heavy Higgs bosons yields an important contribution to the full result for σ x BR

Cross sections with and without interference contributions vs. experimental limits

[E. Fuchs, G. W. '17]



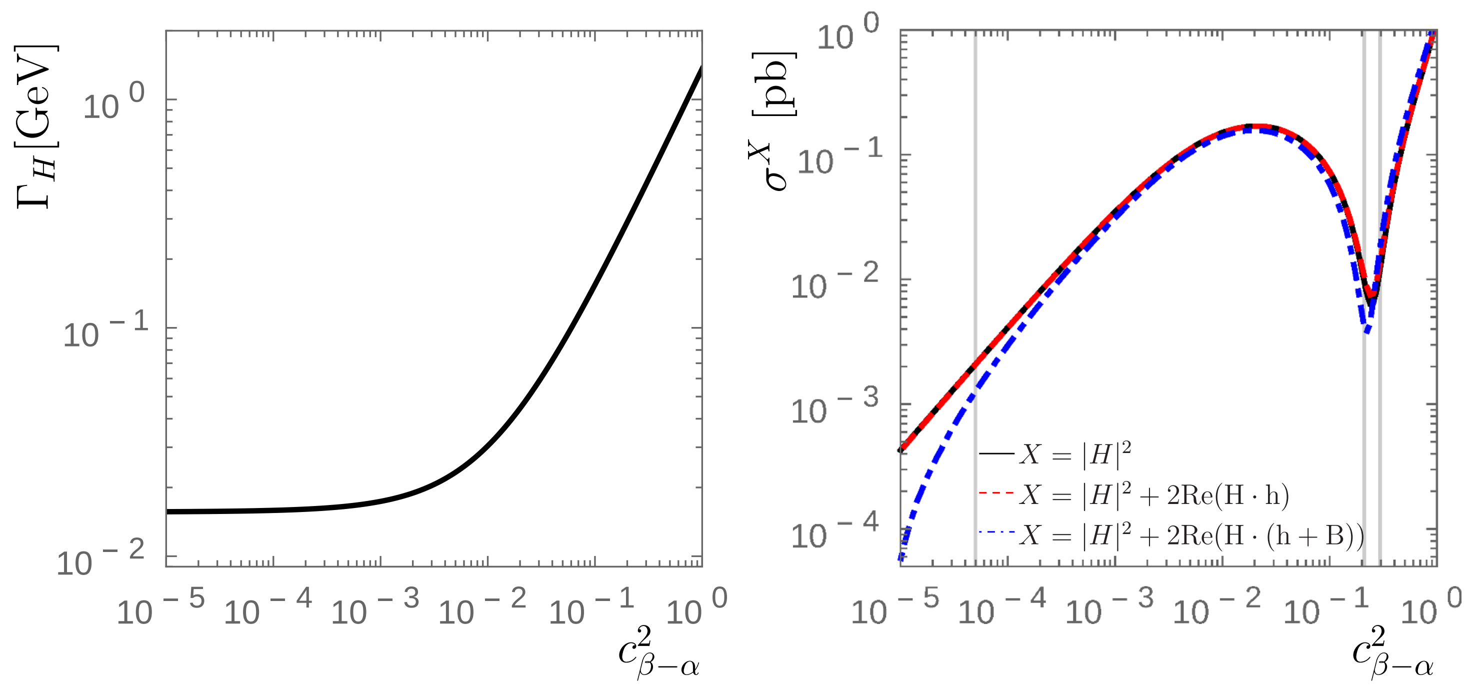


⇒ CP-violating mixing induces resonance-type enhancement + large destructive interference contributions

Generic feature of 2HDM: suppression of couplings to fermions in production process possible

[N. Greiner, S. Liebler, G. W. '15]

▷ Decay $H \to ZZ$ is determined by $g_V^H = \cos(\beta - \alpha) = c_{\beta-\alpha}$



▷ Production $gg \to H$ involves g_t^H and g_b^H with

$$g_t^H = \frac{\sin\alpha}{\sin\beta} = -s_{\beta-\alpha}\frac{1}{\tan\beta} + c_{\beta-\alpha} \approx 0$$

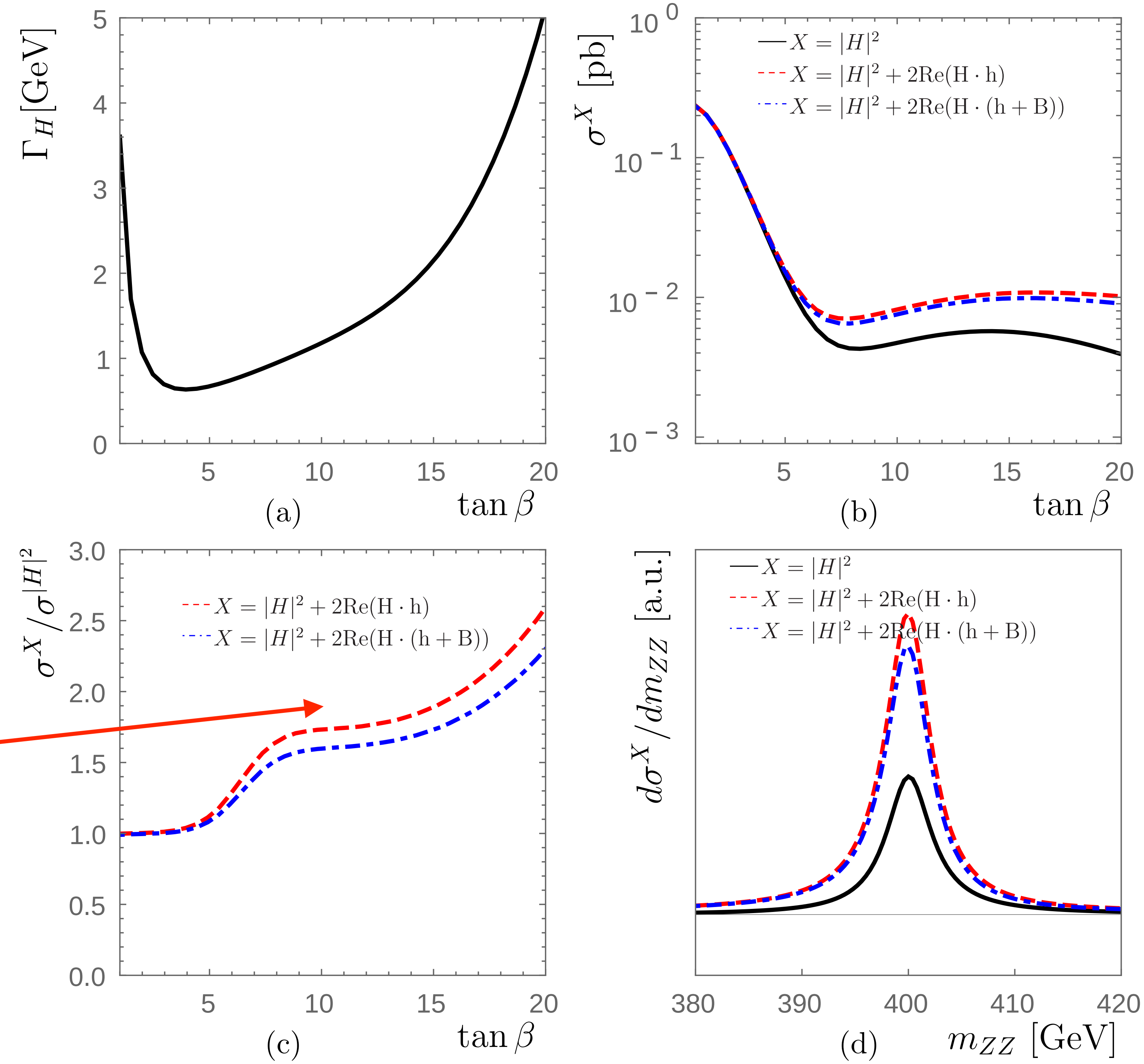
at $\quad c^2_{\beta-\alpha} = 0.2,\ \tan\beta = 2\,.$

$\to$ Where couplings are small (in production or decay) interferences are large.

Hadronic gg → ZZ cross sections, impact of interference contributions for larger values of tanβ

[N. Greiner, S. Liebler, G. W. '15]

sin(β-α) = 0.990, M_H = 400 GeV:



tanβ = 20

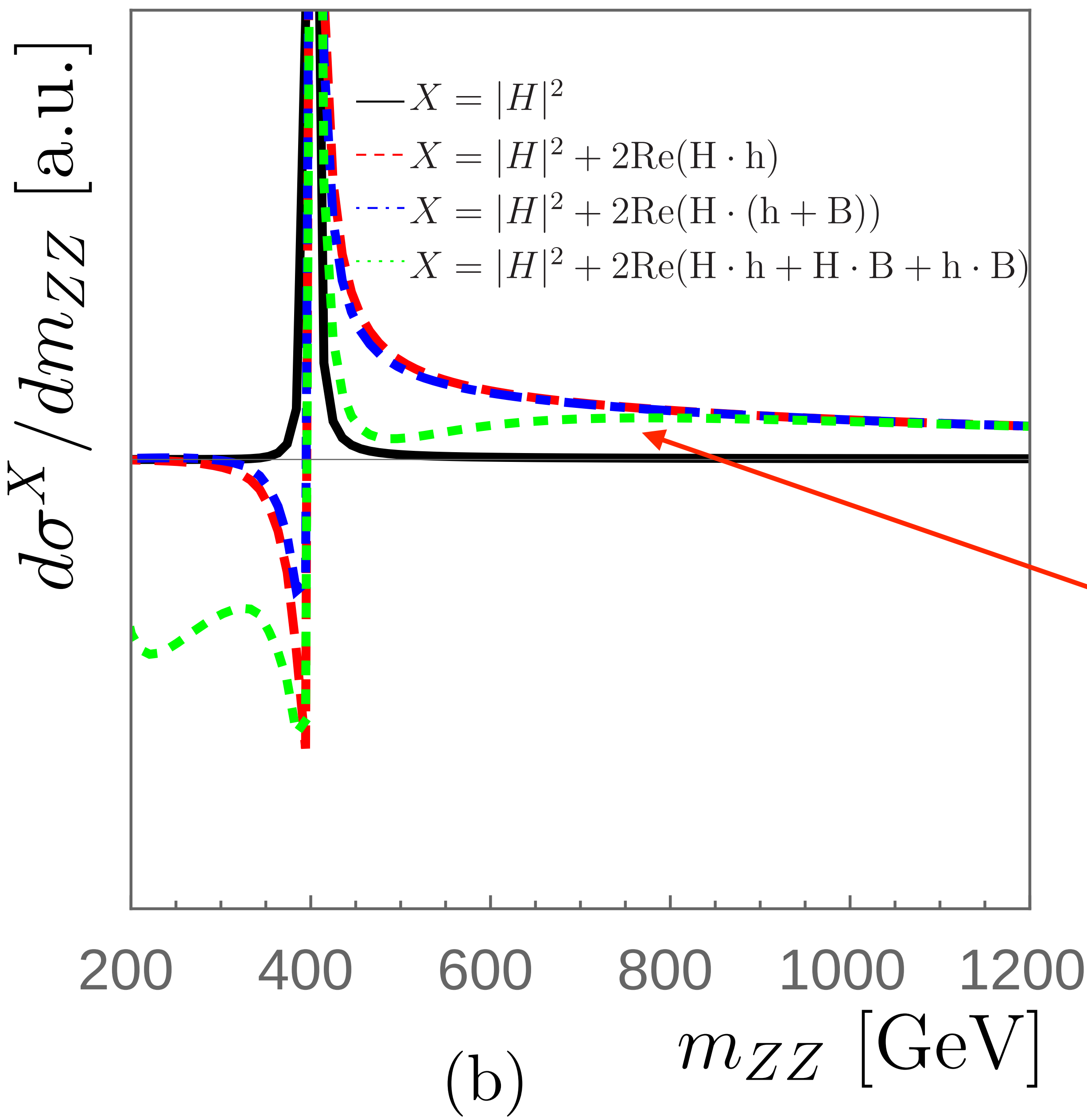
Large constructive contribution from H - h interference!

⇒ Interference effects provide enhanced sensitivity to heavy Higgs H

Interferences at high invariant masses

[N. Greiner, S. Liebler, G. W. '15]

2HDM type I, sin(β-α) = 0.950, M_H = 400 GeV, tanβ = 5:



Interference contributions entering with different sign could mimic peak-like structure!

⇒ All interference contributions needed for correct description